

**SOIL WATER DYNAMICS AND WATER PRODUCTIVITY
OF RICE-WHEAT SYSTEM UNDER DIFFERENT
ESTABLISHMENT METHODS**

Dissertation

Submitted to the Punjab Agricultural University
in partial fulfillment of the requirements
for the degree of

**DOCTOR OF PHILOSOPHY
in
SOIL SCIENCE
(Minor Subject: Agronomy)**

By

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CERTIFICATE – I

This is to certify that the thesis entitled “**SOIL WATER DYNAMICS AND WATER PRODUCTIVITY OF RICE-WHEAT SYSTEM UNDER DIFFERENT ESTABLISHMENT METHODS**” submitted for the degree of **Ph.D**, in the subject of **Soil Science** (Minor Subject: **Agronomy**) of the Punjab Agricultural University, Ludhiana, is a bonafide research work carried out by **Rajan Bhatt (L-2010-A-97-D)** under my supervision and that no part of this thesis has been submitted for any other degree.

The assistance and help received during the course of investigation have been fully acknowledged.

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CERTIFICATE - II

This is to certify that the dissertation entitled, “**SOIL WATER DYNAMICS AND WATER PRODUCTIVITY OF RICE-WHEAT SYSTEM UNDER DIFFERENT ESTABLISHMENT METHODS**” submitted by **Rajan Bhatt (L-2010-A-97-D)** to the Punjab Agricultural University, Ludhiana, in partial fulfillment of the requirements for the degree of Ph.D, in the subject of **Soil Science** (Minor subject: **Agronomy**) has been approved by the Student’s Advisory Committee after an oral examination on the same.

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ABSTRACT

The prevalent wheat-rice cropping system in Punjab has been taking a toll on the natural resources in the region. The wheat and rice grown with conservation technologies need to be studied for the cropping system as a whole. Field experiments were carried out during 2012-14 in a sandy loam soil to assess the role of zero tillage and crop establishment method on crop performance, soil water dynamics, soil physical environment and water productivity of the wheat-rice cropping system. The treatments consisted of zero- (ZTW) and conventional-tillage (CTW) as main, establishment methods viz. direct seeded (DSR) and mechanically transplanted rice (MTR) as sub and tillage in rice viz. puddle (P), conventional (CT) and zero till (ZT) as sub-sub treatments. Zero tillage in wheat and rice did not affect the wheat yield during both the years. The grain yield of DSR was similar to MTR during 2013 but was significantly higher during 2014. The land productivity of wheat-rice cropping system was 15.8 and 11.3 per cent higher in CTW than in ZTW plots during 2012-13 and 2013-14, respectively. It was highest in CTW-DSR-P and lowest in ZTW-MT-ZT. The irrigation water productivity of the system (WP_i) was highest in CTW-MT-P and lowest in ZTW-DSR-ZT. The WP_i of wheat-rice cropping system was significantly higher (16-19.5 per cent) in CTW than in ZTW plots. The WP_i of the cropping system was higher in MTR (0.81-0.88 g kg⁻¹) than DSR (0.60-0.77 g kg⁻¹). The WP_i of wheat-rice cropping system, though similar in CT (0.76 g kg⁻¹) and ZT (0.71 g kg⁻¹) plots of rice during 2012-13, was 11.2 per cent lower in ZT plots during 2013-14. The evapo-transpiration (ET) losses of the wheat-rice cropping system were higher during 2013-14 (971-1057 mm) than in 2012-13 (908-922 mm). The ET losses of wheat-rice cropping system including the intervening period were not affected by tillage in wheat or rice.

Keywords: Cropping system productivity, direct seeded rice, irrigation water productivity, mechanically-transplanted rice, soil water balance, zero tillage

Signature of Major Advisor

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ਪੰਜਾਬ ਵਿੱਚ ਪ੍ਰਚੱਲਿਤ ਕਣਕ-ਝੋਨਾ ਫ਼ਸਲੀ ਪ੍ਰਣਾਲੀ ਦਾ ਇਸ ਖੇਤਰ ਦੇ ਪ੍ਰਾਕ੍ਰਿਤਕ ਸਾਧਨਾਂ ਉਪਰ ਮਾੜਾ ਪ੍ਰਭਾਵ ਪਿਆ ਹੈ। ਸੰਰੱਖਿਅਣ ਤਕਨੀਕਾਂ ਰਾਹੀਂ ਕਣਕ ਅਤੇ ਝੋਨੇ ਦੀ ਪੈਦਾਵਾਰ ਦਾ ਇੱਕ ਪੂਰਨ ਫ਼ਸਲੀ ਪ੍ਰਣਾਲੀ ਵੱਜੋਂ ਅਧਿਐਨ ਕਰਨ ਦੀ ਲੋੜ ਹੈ। ਮੌਜੂਦਾ ਅਧਿਐਨ ਦੌਰਾਨ ਸੰਨ 2012-14 ਵਿੱਚ ਕਣਕ-ਝੋਨਾ ਫ਼ਸਲੀ ਪ੍ਰਣਾਲੀ ਦੀ ਕਾਰਜ ਸਮਰੱਥਾ ਉਪਰ ਬਿਨਾਂ ਵਹਾਈ ਅਤੇ ਫ਼ਸਲ ਸੰਸਥਾਪਨ ਵਿਧੀ ਦੀ ਭੂਮਿਕਾ ਦਾ ਮੁਲਾਂਕਣ ਕਰਨ, ਭੂਮੀ ਜਲ ਸੰਚਾਲਨ, ਮਿੱਟੀ ਦੇ ਭੌਤਿਕ ਵਾਤਾਵਰਣ ਅਤੇ ਜਲ ਉਤਪਾਦਕਤਾ ਵੇਖਣ ਲਈ ਮੈਰਾ ਰੇਤਲੀ ਮਿੱਟੀ ਵਿੱਚ ਖੇਤ ਤਜਰਬੇ ਕੀਤੇ ਗਏ। ਅਧਿਐਨ ਦੌਰਾਨ ਬਿਨਾਂ - (ZTW) ਅਤੇ ਪ੍ਰੰਪਰਾਗਤ ਵਹਾਈ (CTW) ਨੂੰ ਪ੍ਰਮੁੱਖ ਉਪਚਾਰ ਵਜੋਂ, ਸਿੱਧੇ ਤੌਰ ਤੇ ਝੋਨੇ ਦੀ ਬਿਜਾਈ ਦੀ ਵਿਧੀ (DSR) ਅਤੇ ਮਸ਼ੀਨ ਦੀ ਵਰਤੋਂ ਨਾਲ ਝੋਨੇ ਦੀ ਲਵਾਈ (MTR) ਨੂੰ ਉਪ-ਉਪਚਾਰ ਵਜੋਂ ਅਤੇ ਝੋਨੇ ਵਿੱਚ ਵਹਾਈ ਭਾਵ ਕੱਦੂ (P), ਸੁੱਕੀ (CT) ਅਤੇ ਬਿਨਾਂ ਵਹਾਈ (ZT) ਨੂੰ ਉਪ-ਉਪਚਾਰਾਂ ਵਜੋਂ ਵਰਤਿਆ ਗਿਆ। ਅਧਿਐਨ ਦੇ ਦੋਨਾਂ ਸਾਲਾਂ ਦੌਰਾਨ ਕਣਕ ਅਤੇ ਝੋਨੇ ਵਿੱਚ ਬਿਨਾਂ ਵਹਾਈ ਦੇ ਕਣਕ ਦੇ ਝਾੜ ਉਪਰ ਕੋਈ ਪ੍ਰਭਾਵ ਨਹੀਂ ਪਿਆ। ਸੰਨ 2013 ਦੌਰਾਨ DSR ਦਾ ਝਾੜ MTR ਦੇ ਬਰਾਬਰ ਹੀ ਸੀ ਪਰ ਸੰਨ 2014 ਵਿੱਚ ਇਸਦਾ ਝਾੜ ਅਰਥਪੂਰਨ ਤੌਰ ਤੇ ਵਧੇਰੇ ਪਾਇਆ ਗਿਆ। ZTW ਦੇ ਮੁਕਾਬਲੇ CTW ਉਪਚਾਰ ਵਾਲੇ ਪਲਾਟਾਂ ਵਿੱਚ ਕਣਕ-ਝੋਨਾ ਫ਼ਸਲੀ ਪ੍ਰਣਾਲੀ ਦੀ ਭੂਮੀ ਉਤਪਾਦਕਤਾ ਸਾਲ 2012-13 ਅਤੇ 2013-14 ਦੌਰਾਨ ਕ੍ਰਮਵਾਰ 15.8 ਅਤੇ 11.3 ਪ੍ਰਤੀਸ਼ਤ ਵਧੇਰੇ ਪਾਈ ਗਈ। ਭੂਮੀ ਉਤਪਾਦਕਤਾ CTW-DSR-P ਵਿੱਚ ਸਭ ਤੋਂ ਵਧੇਰੇ ਅਤੇ ZTW-MT-ZT ਵਿੱਚ ਸਭ ਤੋਂ ਘੱਟ ਦਰਜ ਕੀਤੀ ਗਈ। ਕਣਕ-ਝੋਨਾ ਫ਼ਸਲੀ ਪ੍ਰਣਾਲੀ ਦੀ ਸਿੰਚਾਈ ਜਲ ਉਤਪਾਦਕਤਾ (WP_1) CTW-MT-P ਵਿੱਚ ਸਭ ਤੋਂ ਵਧੇਰੇ ਅਤੇ ZTW-DSR-ZT ਵਿੱਚ ਸਭ ਤੋਂ ਘੱਟ ਪਾਈ ਗਈ। ZTW ਪਲਾਟਾਂ ਦੇ ਮੁਕਾਬਲੇ CTW ਪਲਾਟਾਂ ਵਿੱਚ ਕਣਕ-ਝੋਨਾ ਫ਼ਸਲੀ ਪ੍ਰਣਾਲੀ ਦੀ ਸਿੰਚਾਈ ਜਲ ਉਤਪਾਦਕਤਾ (WP_1) ਅਰਥਪੂਰਨ ਤੌਰ ਤੇ ਵਧੇਰੇ ਪਾਈ ਗਈ। DSR ($0.60-0.77 \text{ g kg}^{-1}$) ਮੁਕਾਬਲੇ MTR ($0.81-0.88 \text{ g kg}^{-1}$) ਵਿੱਚ ਫ਼ਸਲੀ ਪ੍ਰਣਾਲੀ ਦੀ ਸਿੰਚਾਈ ਜਲ ਉਤਪਾਦਕਤਾ (WP_1) ਵਧੇਰੇ ($16-19.5$ ਪ੍ਰਤੀਸ਼ਤ) ਪਾਈ ਗਈ। ਭਾਵੇਂ ਸਾਲ 2012-13 ਦੌਰਾਨ ਝੋਨੇ ਦੇ CT (0.76 g kg^{-1}) ਅਤੇ ZT (0.71 g kg^{-1}) ਪਲਾਟਾਂ ਦੀ ਸਿੰਚਾਈ ਜਲ ਉਤਪਾਦਕਤਾ (WP_1) ਸਮਾਨ ਸੀ ਪਰ ਸੰਨ 2013-14 ਦੌਰਾਨ ZT ਪਲਾਟਾਂ ਦੀ ਸਿੰਚਾਈ ਜਲ ਉਤਪਾਦਕਤਾ 11.2 ਪ੍ਰਤੀਸ਼ਤ ਘੱਟ ਪਾਈ ਗਈ। ਸੰਨ 2012-13 ($908-922 \text{ mm}$) ਦੇ ਮੁਕਾਬਲੇ 2013-14 ($971-1057 \text{ mm}$) ਦੌਰਾਨ ਕਣਕ-ਝੋਨਾ ਫ਼ਸਲੀ ਪ੍ਰਣਾਲੀ ਵਿੱਚ ਪਾਣੀ ਦਾ ਵਾਸ਼ਪੀਕਰਣ (ET) ਸਭ ਤੋਂ ਵਧੇਰੇ ਹੋਇਆ। ਕਣਕ-ਝੋਨੇ ਫ਼ਸਲੀ ਪ੍ਰਣਾਲੀ ਦੇ ਵਾਸ਼ਪੀਕਰਣ ਉਪਰ ਵਹਾਈ ਦਾ ਕੋਈ ਪ੍ਰਭਾਵ ਵੇਖਣ ਨੂੰ ਨਹੀਂ ਮਿਲਿਆ।

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CONTENTS

CHAPTER	TOPIC	PAGE NO.
I	INTRODUCTION	1 – 4
II	REVIEW OF LITERATURE	5 – 35
III	MATERIALS AND METHODS	36 – 54
IV	RESULTS AND DISCUSSION	55 – 93
V	SUMMARY	94 – 97
	REFERENCES	98 – 122
	VITA	

CHAPTER I

INTRODUCTION

Agricultural sector in India has been and is likely to remain the major consumer of water but the share of water allocated to irrigation is likely to decrease by 10-15 per cent in the next two decades (Singh *et al* 2010). Irrigation is the largest direct human water use, including large amounts of green and blue water required for this sector (Rost *et al* 2008, Döll *et al* 2012). The rice-wheat cropping system (RWCS) is the world's largest agricultural production system occupying 24 million hectares (M ha) throughout India and China alone. The Indo-Gangetic plains (IGP) region of India has RWCS spread over a vast area spanning from Punjab in the Northwest to West Bengal in the East (Singh *et al* 2005). Around 12.3 M ha area in India, 0.5 M ha in Nepal, 2.2 M ha in Pakistan and 0.8 M ha in Bangladesh is under RWCS and around 85 per cent of this area falls in IGP (Ladha *et al* 2003, Timsina and Connor 2001). This cropping system produces more than 45 per cent of the region's food grains and provides staple grains for nearly 42 per cent of the total population (1.3 billion) in South Asia (Jat *et al* 2005). The productivity, profitability and sustainability of rice-based systems are threatened because of the inefficient use of inputs, increasing scarcity of resources especially water and labor, the emerging energy crisis and rising fuel prices. The global water scarcity analysis has shown that up to two-third of the world population will be affected by water scarcity over the next several decades (Wallace and Gregory 2002).

The small states of Punjab and Haryana often referred to as the 'Food Bowl' of the country, produce 50 per cent of the national rice production (Dhillon *et al* 2010). The NASA's gravity mapping satellite "GRACE" recently reported that in north India, the ground water declining at an alarming rate of 0.3 m year⁻¹ in an area of 4,40,000 km² has resulted in the loss of 4 cm ground water year⁻¹ (Soni 2012). Rice in these states is normally flood irrigated during most part of the season with water pumped out from the below-ground aquifers leading to a steady decline in the water table in the region since 1970s (Hira *et al* 2004). The fall in water table particularly in central Punjab, has been reported to increase from 0.2 m year⁻¹ during 1973-2001 to about 1.0 m year⁻¹ during 2000-2006. Majority of the blocks in Punjab are being overexploited for pumping out groundwater (Humphreys *et al* 2010). The lowering of the ground water table in the state has been resulting in an increase in the energy requirement, tubewell infrastructure cost and deteriorating groundwater quality (Hira 2009). Moreover, repeated puddling of coarse and medium textured soils in the state has led to the sub-surface compaction in these soils (Sur *et al* 1981, Kukal and Aggarwal 2003a), which has been proving detrimental for the upland crops like wheat (Kukal and Aggarwal 2003b). The high bulk density layer at 15-20 cm depth formed due to repeated puddling restricts the root growth of wheat in addition to creating aeration stress (Aggarwal *et al* 1995,

Kukal and Aggarwal 2003b). Thus, puddle transplanted system of rice is water-, capital- and energy-intensive and leads to the structural deterioration of the soil.

Another major issue related to RWCS is effective management of rice crop residue, which due to high silica content is not fed to the animals and is normally burnt by the farmers. Burning of rice residues is the predominant method of rice residue disposal especially in the areas under combine-harvesting system. Disposal of crop residues by burning is not a viable option due to losses of soil organic matter, nutrients, C- emissions, intense air pollution and reduced soil microbial activity (Rasmussen *et al* 1980, Kumar and Goh 2000). As per the estimates, 113.6 Mt of rice and wheat residues containing 1.90 Mt nutrients are produced every year in IGP of India (Sarkar *et al* 1999). In Punjab, about 12 Mt of rice straw is burnt annually causing 0.7 Mt of N loss apart from emission of 70 per cent CO₂, 7 per cent CO, 0.66 per cent CH₄ and 2.09 per cent of N₂O (Yadvinder-Singh *et al* 2010). Dobermann and Fairhurst (2002) reported that almost all of the C, 90 per cent of the N, 60 per cent of the S, and 20–25 per cent of the P and K in the rice straw are lost through burning. Studies (Sidhu and Beri 1989, Beri *et al* 1995) have shown that incorporation of rice residues decreased grain yield of wheat from that with removal or burning, due to N immobilization attributable to slow rate of residue decay. Residue incorporation just before rice transplanting results in accumulation of phenolic acids in soil and increases CH₄ emissions under flooded conditions (Grace *et al* 2003). The intensive tillage for wheat seedbed preparation breaks down the aggregates to expose soil organic carbon leading to its loss into the atmosphere (Ashagrie *et al* 2007).

In order to take care of the above-said issues of declining ground water and soil health and residue management in RWCS in the region, various resource conservation technologies (RCTs) viz. laser land leveling, alternate wetting and drying (AWD), irrigation system in rice on fixed day interval or soil matric potential (SMP) based scheduling, mechanical transplanting, zero-tilled wheat and transplanted rice, direct seeded rice, rice and wheat on raised beds, mulching etc. are being advocated for increasing the productivity, sustainability and profitability of this system by reducing the structural degradation of soil, air pollution and increasing water-, labour- and nutrient-use efficiencies. These technologies mainly focus on three fundamental principles of conservation agriculture viz. conservation tillage, use of crop residues (Hobbs *et al* 2008, Jeffery *et al* 2012) as mulch and conservation irrigation (Kukal *et al* 2005).

Rice is conventionally established through tillage under wet conditions with an aim to reduce percolation losses, ease transplanting and suppress weeds. However, its negative effects through structural degradation on upland crops are of concern (Sur *et al* 1981, Aggarwal *et al* 1995, Kukal and Aggarwal 2003a) apart from extensive labour requirement

(300-350 hours ha⁻¹). The alternate tillage practices viz. mechanical transplanting (Raj *et al* 2013, Farooq *et al* 2001), direct seeding of rice under dry (Sharma *et al* 2005) and wet conditions (Gangwar *et al* 2005, Rana *et al* 2014) have been reported to mitigate the negative effects of puddling.

Mechanical transplanting into untilled soils has been shown to be a promising technology for establishing rice in Haryana with large energy and labour saving and regular plant spacing (Sharma *et al* 2005, Malik and Yadav 2008). This could particularly be beneficial in view of increasing labour scarcity in Punjab because of National Rural Employment Guarantee Act (2007) which promises 100-d paid work to the people from villages (Anonymous 2011). However, whether zero-till mechanical transplanting results in water or energy saving in comparison with the puddle transplanted rice is not established yet. There are few studies comparing water use in the puddle and unpuddled transplanted rice. Singh *et al* (2001) observed that in a sandy loam soil, puddled transplanted rice (PTR) consumed 125 mm lower irrigation water than transplanted rice in untilled soil. There is insufficient data on the components of water balance in zero tilled transplanted rice and its water productivity. Moreover, the above-said studies while reporting the irrigation water saving do so in comparison to the farmers practice of irrigation scheduling, who in general have a tendency to over-irrigate. The studies in the region have shown considerable reduction in irrigation water amounts while shifting from continuous flooding till sixty or more number of days to AWD irrigation at fixed interval of two days after complete disappearance of irrigation water (Sandhu *et al* 1980) or on the basis of SMP (Kukal *et al* 2005).

To avoid the use of considerable amount of irrigation water for puddling and continuous flooding till 15 days after transplanting in AWD, direct dry sowing of rice (DSR) at field capacity moisture content has been gaining ground over the last couple of years. Significant saving of irrigation water was reported under AWD at 20 kPa at 20 cm depth in a clay loam soil (Sudhir Yadav *et al* 2011b). This reduction in irrigation water was mainly reported due to reduced seepage losses. Sudhir-Yadav *et al* (2011b) reported significantly higher irrigation water productivity of DSR than PTR but total input water productivity and ET based water productivity were statistically at par at 20 kPa SMP based irrigation scheduling. Very few studies related to detailed water balance characterization in DSR are reported in the literature, particularly in coarse and medium textured soils. Moreover, increased irrigation water productivity of DSR could impact the irrigation water productivity of the following wheat crop, the studies on which are lacking in the literature. Thus, there is need to study soil water dynamics in RWCS as a whole instead of individual crops.

Direct drilling of wheat seeds in untilled soils (Sidhu *et al* 2007, 2008) has long been advocated as zero-tillage technique to reduce the irrigation water amounts and increase the

water productivity (Balwinder Singh *et al* 2011a). Retaining the rice residues as a mulch also offers the potential benefits of reduced water loss due to the suppression of soil evaporation (E_s), suppression of weeds, increased soil organic C, and improved soil structure which finally improves the grain yields (Yadvinder-Singh *et al* 2005). It is well established that mulch can suppress E_s (Al-Darby *et al* 1989, Balwinder Singh *et al* 2011, 2014) which can account for 30–60 per cent of total evapo-transpiration (ET) during wheat production (Siddique *et al* 1990). Zero tillage (ZT) improves the soil physical environment (Bhaduri *et al* 2014, Paccard *et al* 2015) because of residue retention on the fields resulting in increased infiltration rate, water retention, hydraulic conductivity, lower soil compaction (Palese *et al* 2014, Bhaduri *et al* 2014, Zheng *et al* 2015) etc while conventional tillage breaks down the macro-aggregates into micro-aggregates, which adversely affect the soil properties (Roper *et al* 2013, Das *et al* 2014, Kuotsu *et al* 2014). The contradictory results related to zero tillage effects on soil and crops are reported in the literature (Chopra and Chopra 2010, Singh *et al* 2015). It is mainly due to the site-specific conditions including soil type, climatic conditions and cultural practices especially for herbicide use (Singh *et al* 2015). Moreover, zero-tillage impact on preceeding or succeeding crops in the cropping system need to be studied with respect to the land and water productivity of the system as a whole.

Keeping in view these observations, a study was conducted with the following objectives

1. To study the crop performance and water productivities of rice-wheat system under different establishment methods
2. To compute water balance of rice-wheat system under different establishment methods
3. To study the impact of double zero tillage in rice-wheat cropping system on soil physical environment and soil water dynamics

CHAPTER II

REVIEW OF LITERATURE

The pertinent works related to the present study entitled “**Soil water dynamics and water productivity of rice-wheat system under different establishment methods**” have been reviewed in this chapter under the following heads

2.1 RICE-WHEAT CROPPING SYSTEM ISSUES

2.1.1 Declining water resources

2.1.2 Degrading soil health

2.1.3 Environment degradation

2.2 IMPACT OF CROP ESTABLISHMENT AND CONSERVATION TILLAGE TECHNIQUES ON CROP PERFORMANCE

2.2.1 Rice

2.2.1.1 Mechanical transplanting of rice

2.2.1.2 Direct seeding of rice

2.2.2 Wheat

2.2.2.1 Zero till wheat

2.3 IMPACT OF CROP ESTABLISHMENT AND CONSERVATION TILLAGE TECHNIQUES ON IRRIGATION WATER USE AND WATER PRODUCTIVITY

2.3.1 Rice

2.3.1.1 Mechanical transplanting of rice

2.3.1.2 Direct seeding of rice

2.3.2 Wheat

2.3.2.1 Zero till wheat

2.4 IMPACT OF CROP ESTABLISHMENT AND CONSERVATION TILLAGE TECHNIQUES ON SOIL PHYSICAL ENVIRONMENT

2.4.1 Rice

2.4.1.1 Mechanical transplanting of rice

2.4.1.2 Direct seeding of rice

2.4.2 Wheat

2.3.2.1 Zero till wheat

2.1 RICE-WHEAT CROPPING SYSTEM ISSUES

The introduction of green revolution technologies in the mid 1960s resulted in high growth rates of food grain production (wheat 3 per cent, rice 2.3 per cent), which kept pace with population growth (Fischer *et al* 2011). However, beginning in the 1980s, annual growth rates in rice and wheat yields declined to about 1 per cent annually in recent years. Evidence

is now appearing that rice-wheat system productivity is plateauing because of a fatigued natural resource base, including the effects of adverse changes in climatic conditions (Pathak *et al* 2003, Ladha *et al* 2003). Thus, the region's food security is continuously threatened and the emerging challenges of post-Green Revolution (GR) agriculture pose additional hurdles. Additionally, in many of the areas of the Eastern Indo-Gangetic Plains, which are located in unfavorable rice ecosystems, the potential gains from GR technologies seem not to have reached the lives of millions. Global environmental changes have further complicated the already fragile and vulnerable food security in South Asia (Fischer *et al* 2011).

The rice–wheat (RW) cropping system of north-west India is backbone to India's food security (Timsina and Connor 2001), with the states of Punjab and Haryana producing 50 per cent of rice and 85 per cent of the wheat. Low levels of soil organic matter, appearance of multiple nutrient deficiencies due to their over-mining from the soils and poor management of crop residues (CRs), leading to their burning are some of the major reasons for declining RW productivity in the region (Ladha *et al* 2000). The productivity of these systems needs to increase to keep up with population growth in India, which is predicted to increase from 1.12 billion in 2008 to 1.35 billion by 2025 (UNEP 2008). However, in recent years, the sustainability of RW system has been questioned with yield stagnation (Ladha *et al* 2003), declining underground water table (Humphreys *et al* 2010, Hira *et al* 2004), soil degradation (Bhandhari *et al* 2002) and atmospheric pollution (Bijay- Singh *et al* 2008). Furthermore, intensive RW system causes increased incidence of pests and diseases, increasing labour scarcity, salinity, and water-logging in some regions (SW Punjab) (Chhokar and Sharma 2008, Singh 2000, Humphreys *et al* 2010). In order to take care of the above-said issues of RW cropping system in the region, various resource conservation technologies (RCTs) viz. laser land leveling (Bhatt and Sharma 2010), alternate wetting and drying in rice either on fixed day interval (Sandhu *et al* 1980) or soil matric potential (SMP) basis (Kukul *et al* 2005), zero-till wheat, direct seeded rice (Sudhir-Yadav *et al* 2007, Bhatt and Kukul 2015), rice and wheat on raised beds, mechanical transplanting of rice in tilled and untilled conditions (Kamboj *et al* 2013, Bhatt and Kukul, 2014), mulching etc. are being advocated for increasing the productivity, sustainability and profitability of the system by reducing the structural degradation of soil, air pollution and increasing water-, labour- and nutrient-use efficiencies. These technologies mainly focus on three fundamental principles of conservation agriculture viz. conservation tillage, use of crop residues (Bhatt and Khera 2006, Hobbs *et al* 2008) as mulch and conservation irrigation (Kukul *et al* 2005, Sudhir -Yadav *et al* 2011b). These technologies, however, need to be evaluated and refined especially from water management point of view so as to be really water-efficient. Some of these technologies viz. direct-seeding of rice, direct-drilling of wheat and mechanically transplanting of rice are

being advocated as the potential irrigation water-saving techniques apart from being labor-saving as well. However, there is a need to evaluate their performance in improving the declining crop and water productivities in texturally divergent soils under different agro-climatic regions. At present, the sustainability and profitability of the rice-wheat cropping system of the region is mainly affected by the declining water resources, degrading soil health and environment.

2.1.1 Declining water resources

In Asia, where water has always been regarded as an abundant resource, its per capita availability declined by 40-60 per cent between 1955 to 1990; projections of the International Rice Research Institute, Manila, suggest that most Asian countries will have some water problems by the year 2025 (IRRI 1995). Agriculture in Asia accounts for 86 per cent of the total annual water withdrawals compared with 49 per cent in North and Central America and 38 per cent in Europe. Irrigated rice, in particular, is a heavy consumer of water; it takes 5000 litres of water to produce 1 kg rice and rice-wheat cropping system consumes about 11,650 m³ ha⁻¹ water out of which 7650 m³ ha⁻¹ is by rice (IRRI 1995). Thus, the water table in some pockets of India is declining down at an alarming rates while in others, the rising water table is creating salinity/sodicity. Jagannath (2000) pointed out that in some parts of Haryana, the water table is rising at a rate of 10-30 cm year⁻¹ and the reasons may include seepage from the canals, water courses, deep percolation and development of perched water table due to an impermeable layer.

South Asia is a region with limited land and water resources to support its huge population. The South Asian countries constitute about one-fourth of the world's total population, but have only about 4.5 per cent (1945 BCM) of the world's annual renewable water resources (RWR) of 43,659 BCM (Ali *et al* 2012). Except for Bhutan and Nepal, the per capita water availability in the region is lower than the world average, with water use in this region being limited mainly to the agriculture sector. The per capita availability of water in India, as a whole, has decreased to 1869 from 4000 m³ in the last two decades. By 2025, the per capita water availability could fall below 1000 m³ (UNEP 2008). Water shortages are set to intensify as the region's population is projected to increase significantly over the next 50 years and climate change adds further uncertainty (Ali *et al* 2012, FAO 2011). The annual precipitations are about 1083, 2666, 4000, 80, 1500, 1712, and 2091 mm in India, Bangladesh, Bhutan, Pakistan, Nepal, Sri Lanka, and Myanmar, respectively. There is an excess of surface water during the summer months and the water shortfalls during winters, due to which the management of groundwater, surface storage, and irrigation systems is of utmost importance for agriculture in SA (Ali *et al* 2012). Estimated water resources of India, the largest country of SA, include about 4000 km³ of precipitation, 500 km³ of water enters

the country, and total actual RWR are 1869 km³ of water (MWR 2009). It has been estimated that only about 1123 km³, including 690 km³ from surface water and 433 km³ from groundwater resources, can be put to beneficial use (MWR 2009). In terms of total RWR, India stands first with an availability of 1911 km³ followed by Bangladesh (about 1200 km³), Pakistan (223 km³), Bhutan (78.0 km³), and Sri Lanka (52.8 km³) (FAO 2011). Water table in some parts of NW India and Pakistan has declining by an average rate of 40.0 ± 10 mm year⁻¹ between 2002 and 2008 (Rodell *et al* 2009, Hira 2009, Shakir *et al* 2011). It is estimated that the water resources will be scarce in SA, which will be using 41 per cent of its RWR by 2030. The issues and challenges with respect to the development of water resources in SA are diverse and complex due to poor and often uneven endowment of water. The SA has the potential to develop the water resources in such a way that can reduce the vulnerability to climate change as well as to develop the economy.

The rate of fall of underground water has considerable increased over the last few decades (Humphreys *et al* 2010, Hira *et al* 2004) and the intensive rice-wheat cropping system mainly blamed for this depletion. Centrifugal pumps are now proving to be less efficient because of their inefficiency to withdraw water from the deeper depths. Hence, the farmers are shifting to submersible pumps, which are costly and require more energy to extract water from the deeper depths (Hira *et al* 2004). The increase in water table depth has accelerated alarmingly in some areas in recent years; for example, in parts of Ludhiana district in central Punjab, the rate of fall increased from about 0.2 m yr⁻¹ during 1973–2001 to about 1 m yr⁻¹ during 2000–2006 (Humphreys *et al* 2010). In 2009, 103 out of 138 administrative blocks were overexploited in Punjab, while 55 out of 108 blocks were overexploited in Haryana (http://cgwb.gov.in/gwprofiles/st_Haryana.htm). The increase in depth to the groundwater in north-west India has three major negative effects (Hira 2009): (1) higher energy requirement and cost of pumping groundwater; (2) increasing tubewell infrastructure costs; and (3) deteriorating groundwater quality, which will ultimately be to the degree that the groundwater becomes unusable because of upwelling of salts from the deeper native groundwater (Kamra *et al* 2002), and because of saline groundwater intrusion into fresh groundwater (as a result of reversal of groundwater flows due to the lowering of groundwater levels in fresh groundwater regions below levels in areas with saline groundwater).

India, the largest groundwater user in the world (230 km³ yr⁻¹), more than a quarter of the global total water use (Tyagi *et al* 2012). Nationally, the area under GW irrigation has increased by 6-times over the last six decades (1950-51 to 2005-06) in contrast to the declined share of water in agriculture because of increased demand of non-agricultural sectors (Tyagi *et al* 2012). The NASA's gravity mapping satellite "GRACE" tracks the local gravity field of

an area on the assumption that if we remove much of ground water, there is a loss of mass which further results in the decrease of the gravity. Recent reports of the satellite showed that in north India ground water declined at an alarming rate of 1 ft year⁻¹, in an area of about 440,000 km² which further resulted in the loss of 4 cm loss of raw ground water or 18 km³ year⁻¹ (Soni 2012).

In view of depleting ground water (GW) in the region (Hira *et al* 1998) besides a current annual water deficit of ~1.27 M ha-m (Jain and Kumar 2007) owing to escalated water demand from 2.76 to 4.76 M ha-m during the last four decades (Minhas *et al* 2010), there is a need to address the issues relating sustainable crop production and rational water use.

2.2.2 Degrading soil health

In the rice-wheat cropping system, rice is conventionally established through tillage under wet conditions with an aim to reduce percolation losses, ease transplanting and suppress weeds. Tabbal *et al* (2002) considered that puddling in central Luzon, Philippines, is done primarily for weed control, whereas Kukal and Aggarwal (2003a) placed more emphasis on its role in reducing percolation losses in north-west India, where soils are highly permeable. Further, it was observed that puddling is not essential for rice growth and yield, with many studies (but not all e.g. Singh *et al* 2001) reporting similar yields for transplanted or direct seeded rice with and without puddling. The extent of the reduction in percolation losses depends on puddling intensity. However, its negative effects through structural degradation on upland crops are of concern (Aggarwal *et al* 1995, Kukal and Aggarwal 2003b). Repeated puddling of coarse and medium textured soils has led to the sub-surface compaction in these soils (Sur *et al* 1981, Kukal and Aggarwal 2003a) which has been proving detrimental for the upland crops like wheat (Kukal and Aggarwal 2003b).

The puddling is not must for rice cultivation at many places of high yielding rice cultural systems of Australia and California, USA. Kumar *et al* (2005) and Reddy *et al* (2005) have shown that puddling can be avoided in transplanted rice culture. The destruction of soil aggregates by puddling leads to the formation of surface crusts and cracks on drying, delaying preparation of a seedbed for ensuing crops. When broken by tillage, the resulting large clods provide poor contact with seed, thereby restricting germination of succeeding upland crop. Thus puddle transplanted system of rice is water, capital and energy intensive and leads to structural deterioration of the soil. During wheat establishment, conventional seed bed prepared by extensive tillage operations after burning of rice straw followed by planking which break macro-aggregates into the micro-aggregates which adversely affect the soil properties (Roper *et al* 2013, Das *et al* 2014, Kuotsu *et al* 2014).

According to Singh (2000) in Haryana 3 per cent of soil in 1980 had a low P content and by 1995 a low P content was found in 73 per cent of the soils, whilst the area with low N

content only increased from 89 to 91 per cent. Soils with a high K content have decreased from 91 per cent in 1980 to 61 per cent in 1995. The wheat–rice rotation is disturbing the balance of available nutrients in the soil and also causing a deficiency of micronutrients, particularly zinc and copper (Gill 1992). Continuous removal and burning of crop residues can lead to net losses of nutrients under standard fertilization practices, which ultimately will lead to higher nutrient cost input in the short term and reduction in soil quality and productivity in the long term.

2.2.3. Environment degradation

In India, over 500 million tons (Mt) of agricultural residues are produced every year (MNRE 2009; www.nicra.iari.res.in/Data/FinalCRM.doc). The majority of the rice and wheat in Punjab is combine harvested, leaving anchored straw 0.3-0.6 m high and loose straw in windrows. Management of the rice stubble (more than 7 t ha⁻¹) is a major problem in the system. Burning is widely practiced by the farmers being easy and quick method of disposing off of rice residues (> 17 Mt year⁻¹) thereby causing air pollution (Gupta *et al* 2004), burning of tremendous amount of nutrients and degrading soil physical and biological health (Samra *et al* 2003, Yadvinder-Singh and Singh 2014). With increased production of rice and wheat, residue production has also increased substantially. Cereal crops (rice, wheat, maize, millets) contribute 70 per cent of the total crop residues (352 Mt) comprising 34 per cent by rice and 22 per cent by wheat crops. The RW system accounts for nearly one-fourth of the total crop residues produced in India (Sarkar *et al* 1999). The surplus crop residues (i.e., total residues produced minus the amount used for various purposes) are typically burned on-farm. The amount of surplus crop residues available in India is estimated between 84 and 141 Mt year⁻¹ where cereals crops contribute 58 per cent. Of the 82 Mt of surplus crop residues nearly 70 MTs (44.5 Mt rice straws and 24.5 Mt wheat straws) are burned annually which causes severe air pollution and loss of nutrients being present in crop residues.

According to Jain *et al* (2014) rice straw contributed 40 per cent of the total residue burnt followed by wheat straw (22 per cent) and sugarcane trash (20 per cent). They further quantified that during 2008–09 burning of crop residues emitted 8.57 Mt of CO, 141.15 Mt of CO₂, 0.037 Mt of SO₂, 0.23 Mt of NO₂, 0.12 Mt of NH₃ and 1.21 Mt of particulate matter for the year. Crop residues are good sources of plant nutrients. About 40 per cent of the N, 30-35 per cent of the P, 80-85 per cent of the K, and 40-50 per cent of the S absorbed by rice remain in the vegetative parts at maturity (Dobermann and Fairhurst 2002). Similarly about 25-30 per cent of N and P, 35-40 per cent of S, and 70-75 per cent of K uptake are retained in wheat residue. Typical amounts of nutrients in rice straw at harvest are 5-8 kg N, 0.7-1.2 kg P, 12-17 kg K, 0.5-1 kg S, 3-4 kg Ca, 1-3 kg Mg, and 40-70 kg Si per ton of straw on a dry weight basis (Dobermann and Witt 2000). One ton of wheat residue contains 4-5 kg N, 0.7-0.9 kg P,

and 9-11kgK (Yadvinder-Singh, personal communication). Based on several observations, Van Duivenbooden (1992) reported mean N, P and K amounts in rice straw as 6.2 kg N, 1.1 kg P and 18.9 kg K per ton of straw. Potassium concentration is generally higher (up to 25 kg per ton) in rice straw of NW IGP than that from other regions of the India or other countries. The amount of NPK contained in rice and wheat residues produced (197 Mt) is about 4.1×10^6 Mt in India. Considering 90 per cent of rice straw and 30 per cent of wheat straw are surplus in Punjab, the amount of NPK recycled annually would be about 0.54 MT. Besides NPK, one ton of rice and wheat residues contain about 9-11 kg S, 100 g Zn, 777 g Fe and 745g Mn. crop residues still play an important role in the cycling of nutrients despite the dominant role of chemical fertilizers in crop production.

The increases achieved by the Green Revolution have created several environmental problems, viz. deforestation, waterlogging, salinity, alkalinity, soil erosion and decline and rise of the ground water table linked to brackish water, etc. These environmental problems became evident in the 1980s, and are becoming increasingly prominent through time (Singh 1997, Kumar and Pasricha 1999). Large parts of the land are degraded by desertification, soil salinity, waterlogging, floods, and droughts, due to inefficient agricultural practices, and deforestation has caused excessive soil erosion (Gill 1992, Randhawa 1992). The field burning of crop residues is a major contributor to reduced air quality (particulates, greenhouse gases), human respiratory ailments, and the death of beneficial soil fauna and microorganisms. Apart from loss of carbon, up to 80 per cent loss of N and S, 25 per cent of P and 21 per cent of K occurs during burning of crop residues (Yadvinder-Singh *et al* 2005). Solution to avoid burning of rice straw would be to use it as a mulch material in the following wheat to improve crop yields, conserve soil moisture, and save environment.

2.2 Impact of crop establishment and conservation tillage techniques on crop performance

2.2.1 Rice

2.2.1.1 Mechanical transplanting of rice

Labour shortage is an emerging issue in the prevailing RW cropping system due to narrow window period and legal binding to transplant paddy after 10th of June which needs to be addressed for the sustainability and profitability of the RW cropping system in the region (Bhatt and Kukal 2014, 2015, Humphreys *et al* 2010). The labor scarcity has been increasing over the last few years due to assured work under MANREGA scheme of Govt. of India (GOI 2011). Thus, to solve the labor shortage during the peak transplanting period, mechanical transplanting of rice (MTR) is one option (Garg *et al* 1997, Prasad *et al* 2001, Kamboj *et al* 2013, Bhatt *et al* 2014) as manual transplanting is laborious and time-consuming requiring about 300-350 man-hr ha⁻¹, which is roughly 25 per cent of the total labour requirement of

rice production. Transplanting at right time has a pronounced influence on rice yield. On an average, a worker dips fingers 1,40,000 times to transplant one acre of land and can transplant only 0.016 ha day⁻¹ (Rao and Pardhan 1973). They further reported that a delay in transplanting of one month reduces the yield by 25 per cent and delay of two months reduces it by 70 per cent. Further, the plant population of rice remains quite low in manual transplanting compared to the recommended plant density. In order to compensate for lower plant population, farmers often use excessive nitrogenous fertilizer to encourage tillering, which generally results in complex problems of insect-pests and diseases and ultimately lowers the crop yields. However, to avoid ill effects of puddling, including over-use of irrigation water, mechanical transplanting in dry cultivated (Singh *et al* 2005, Duraisamy *et al* 2011) or in uncultivated soils is being advocated as a good option (Malik and Yadav 2008, Sharma *et al* 2003, 2005). The MTR must be adopted in the region facing labour shortage problems even though yield in manual transplanting is reported to be somewhat higher (though statistically at par) with (4.87 t ha⁻¹) than mechanical transplanting (4.85 t ha⁻¹) (Pandirajan *et al* 2006).

Mechanical transplanting (MT) under conventional tillage can save 66 per cent of transplanting cost and 93 per cent of transplanting time as compared to the manual transplanting (Sharma *et al* 2002). The mechanical transplanting of rice with self propelled rice transplanter helps in obtaining highest grain yields as compared to the manual transplanting and direct seeding of rice (Singh *et al* 2005) because of early establishment, uniform growth owing to uniform placement of seedlings at a uniform depth and spacing with equal number of seedlings per hill, which significantly influence the plant height, total panicles m⁻², effective panicles m⁻², grains panicle⁻¹ and 1000-grain weight. A large number of on-farm trials were conducted at farmers' fields in Haryana, India, from 2006 to 2010 to evaluate the performance of the MTR under nonpuddled and no-till situations as compared to conventional puddled transplant rice (PTR) and it was revealed that compared with PTR, the non-puddled MTR produced 3 - 11 per cent higher grain yield in different years (Kamboj *et al* 2013).

Kukal *et al* (2014) reported that crop performance in MTR under puddled condition had an edge over the DSR under conventional tillage while chlorophyll index was reported to be significantly at par with MTR-puddle, MTR-zero till and PTR while the were found to be significantly better over the DSR treatments. However, fertility percentage was found to be significantly better in PTR and MTR plots over that in DSR plots. Similar was the trend for 1000-grain weight which ultimately contributes to the grain yields. They further reported that in sandy loam soil MTR in puddle conditions performed similar to conventional PTR.

However, the crop yield decreased when rice seedlings were mechanically transplanted in zero-tilled soil.

Mohanty *et al* (2010) concluded that labour requirement in case of self-propelled rice transplanter was 40 man-h ha⁻¹ and in case of manual random transplanting it was 224 man-h ha⁻¹. They further observed that the average cost of transplanting was Rs 1554 ha⁻¹ in case of self-propelled rice transplanter and Rs 2675 ha⁻¹ in case of traditional method. Benefit-cost ratio in case of rice transplanter and manual transplanting was 2.38:1 and 1.77:1 respectively. Therefore MTR resulted in higher benefit cost ratio of 34.46 per cent as compared to manually hand transplanted rice (PTR).

Tripathi *et al* (2004) at Orissa evaluated self propelled transplanter and manual random transplanting and reported significantly higher number of effective tillers m⁻² and grain yield under self propelled transplanter as compared to the manual transplanting. Din *et al* (2008) in Portblair compared six-row manual transplanter with line transplanting at 20×20 cm spacing and found significantly higher number of hills m⁻² resulting in higher grain yield in line spacing. However, Kasaby *et al* (2002) observed higher number of panicles m⁻², grains panicle⁻¹, grain yield and straw yield under mechanical transplanting as compared to the manual transplanting.

Singh *et al* (2005) at Modipuram reported that MT with self propelled transplanter resulted in early establishment, uniform growth owing to uniform placement of seedlings at a uniform depth and spacing with equal number of seedlings per hill. The crop utilized different resources in a better way and produced taller plants, higher 1000-grain weight, grains panicle⁻¹, tillers m⁻² and finally higher grain yields as compared to manual transplanting and direct seeded rice.

Hugar *et al* (2009) at Bangalore while comparing zero tillage, normal transplanting, drum seeder and mechanical transplanting, observed non-significant effect of crop establishment on plant height, total tillers m⁻², effective tillers m⁻² and finally grain yield. The results were further confirmed by Singh *et al* (2005) at Modipuram, U.P. with non-significant effect of crop establishment viz. manual and mechanical transplanting on plant height, plant dry matter, panicles m⁻², panicle length, grains panicle⁻¹ and grain yield. Kim *et al* (1999) at Korea in a field study reported that MTR gave similar yields as obtained in the direct seeding of rice.

Sharma *et al* (2007) at Bihar, reported that mechanical transplanting of rice with self propelled rice transplanter (5.95 t ha⁻¹) and manual transplanting (5.98 t ha⁻¹) were at par to each other but produced significantly higher grain yield than direct seeding of rice while Singh *et al* (2006) at Uttar Pradesh found that mechanical transplanting of rice significantly

increased the grain yield by 20, 24 and 39 per cent over manual transplanting, direct dry sowing and direct sowing of sprouted seeds in the puddle conditions, respectively.

In a four year study conducted at Modipuram, to access the effect of rice establishment methods viz. MT in puddle, unpuddled and manual transplanting, Gangwar and Singh (2010) observed that dry matter accumulation and leaf area index were significantly higher under MTR-puddle than manual transplanting of rice. It was further observed that the number of panicles m^{-2} and number of grains panicle $^{-1}$ were significantly higher in MTR-puddle than manual transplanting of rice but the differences with respect to 1000-grain weight were non-significant.

Singh *et al* (2005) reported that mechanical transplanting of rice with self-propelled rice transplanter resulted in highest grain yield compared to manual transplanting and direct seeding of rice. Early establishment, uniform growth owing to uniform placement of seedlings at a uniform depth and spacing with equal number of seedlings per hill under mechanical transplanting significantly resulted in higher grain yield. In Haryana, mechanized transplanting of all type of rice cultivars has been successful in un-puddled and no-till situations with long-term sustainability in the double no-till rice-wheat system (Kamboj *et al* 2013).

Sharma *et al* (2002) observed that mechanical transplanting by self-propelled transplanter produced similar grain yields as with the manual transplanting but produced significantly higher grain yield than in direct sowing both under dry and wet conditions. This was attributed to the higher number of seedlings hill $^{-1}$ planted through mechanical transplanter producing significantly higher number of effective tillers m^{-2} , higher 1000-grain weight and the grain yield. The energy requirements for mechanical and manual methods of transplanting were found to be 1074 and 757 MJ ha $^{-1}$, respectively, while the yield of mechanically transplanted paddy was found to vary from 3.75 to 5.70 t ha $^{-1}$ with an average yield of 4.71 t ha $^{-1}$ in comparison to 4.5 t ha $^{-1}$ in manually transplanted paddy (Baruah *et al* 2001).

Regarding the yield comparison by transplantation methods, the innovator farmers reported that mechanically transplanted fields yielded 0.55 t ha $^{-1}$ higher as compared with the manually transplanted fields (Farooq *et al* 2001). Pandiarajan *et al* (2006) reported that transplanting with power transplanter resulted in highest benefit cost ratio. Rani and Jayakiran (2010) reported that seedling throwing and mechanical transplanting along with Arbuscular Mycorrhizal Fungi (AMF) inoculation of seedling may be recommended wherever the labour is scarce and costlier for getting higher yields and net income. Further, it was found that MTR helps in efficient use of resources by saving upon labour (20 persons-day ha $^{-1}$), cost saving (Rs 1500 ha $^{-1}$), water savings upto 10 per cent along with higher productivity of 0.5 to 0.7 t ha $^{-1}$ as compared to traditional methods of rice transplanting (Malik *et al* 2011). A field

trial conducted by Sharma *et al* (2007) at Bihar to compare different establishment methods revealed that the self propelled transplanter yielded maximum net returns (Rs. 44,559 ha⁻¹) and benefit: cost ratio (1.47). Similarly Singh *et al* (2005) carried out a field experiment at Modipuram to compare different establishment methods and reported that mechanical transplanting was most effective with specific cost (Rs 2.27 kg⁻¹) and provided maximum benefit-cost ratio (2.34), whereas manual transplanting was the least beneficial due to its high cost of production (Rs 15,400 ha⁻¹) which resulted in maximum specific cost (Rs 2.66 kg⁻¹) and lowest benefit-cost ratio (1.97). In another study, Sharma *et al* (2002) reported higher output:input ratio (2.53) with self-propelled transplanter over conventional manual transplanting (2.05) and proved more remunerative than the other methods of rice establishment. They further reported that MTR saved 65.9 per cent cost of transplanting as compared to manual transplanting. At Pantnagar, Sharma and Singh (2008) studied the development and performance evaluation of a mat type nursery raising device and reported that cost of raising mat type nursery for one hectare (400 mats) was Rs 300 as compared to Rs 1,609 with manual method of nursery raising. A field experiment was conducted at Gangavathi (Karnataka) by Manjunatha *et al* (2009) to study the possibility of mechanizing transplanting operations in paddy crop with a view to reduce the cost of cultivation. They reported that cost of MTR was only Rs 789 ha⁻¹ as compared to Rs 1625 ha⁻¹ in case of manual transplanting. Similarly, Kumar *et al* (2008) from Birsa, Ranchi (Jharkhand) reported that by adopting MTR, the cost of transplanting including nursery raising was Rs 1200 ha⁻¹ lower than that with conventional system of rice transplanting.

Mohanty *et al* (2010) observed that the grain yield in both manual and mechanical transplanted rice remained at par with mean grain yield of 4.14 and 3.48 t ha⁻¹, respectively. Further, they reported that benefit-cost ratio in case of rice transplanter and manual transplanting was 2.38:1 and 1.77:1, respectively. Therefore, mechanically transplanted rice gave higher benefit cost ratio of 34.5 per cent as compared to hand transplanted rice.

Sharma *et al* (2004) observed that mechanical transplanting was at par with manual transplanting as far as grain and straw yield were concerned but was statistically higher over the DSR. They also observed that mechanical transplanting was most cost-effective and energy-efficient requiring lowest specific energy. On the other hand, some workers (Gangwar *et al* 2008) found DSR to be better in comparison to the mechanical transplanting as unpuddled conditions had more plant population per unit area due to better dry/wet tillage in unpuddled conditions over the puddled conditions. The performance of rice transplanter under nonpuddled (after cultivation in dry soil conditions) and no-till situations has been reported better than conventional puddle systems earlier as well (Yadav *et al* 2010). Kamboj *et al* (2013) reported that compared with PTR, non-puddled MTR produced 3-11 per cent higher

grain yield from 2006-2010. Further, Chauhan and Abugho (2013) stated that even in the case of similar yield between PTR and MTR systems, the MTR system will help in reducing labor requirement and ultimately, will increase overall profits of farmers.

The reviewed literature shows that mechanical transplanting helps in labor and energy saving, but studies especially in dry cultivated and untilled soils need to be studied in texturally divergent soils under different agro-climatic conditions (Bhatt and Kukal 2014). Moreover, such studies need detailed comparisons of water balance parameters between MTR both in dry tilled and untilled soils.

2.2.1.2 Direct seeded rice

Dry seeding provides another mechanical and potentially simpler option for establishment of rice than mechanical transplanting (Bhatt and Kukal 2015). In dry seeded rice (DSR), the seed is normally drilled into the soil at field capacity moisture and tilled in a similar way to conventional tillage for wheat, but it can also be sown in untilled soils (Bhushan *et al* 2007). The conventional system of puddling results in deterioration of soil structure and formation of sub-surface hard pan (Kukal and Aggarwal 2003a) which caused a yield decline in the succeeding wheat crop (Kukal and Aggarwal 2003b). Also the PTR has resulted in declining water table over the years, there has been a shift from PTR to DSR cultivation in several countries of South-east Asia (Pandey and Velasco 2000). In Asia, dry seeding is extensively practiced in rainfed lowlands, uplands, and flood-prone areas, while wet seeding remains a common practice in irrigated areas (Azmi *et al* 2005, De Dios *et al* 2005). Direct seeding in saturated soil has been widely adopted in southern Brazil, Chile, Venezuela, Cuba, some Caribbean countries, and in certain areas of Colombia (Fischer and Antigua 1996). Direct seeding also offers the option to resolve edaphic conflicts (between rice and the subsequent non-rice crop) and enhance sustainability of the rice-based cropping system and succeeding winter crops (Farooq *et al* 2008, Singh *et al* 2005) in India.

The crop yield in DSR is often reported to be lower than in PTR principally due to poor crop stand, high per centage of panicle sterility, higher weed and root-knot nematode infestation (Singh *et al* 2005, Bhatt and Kukal 2015). The yield loss with DSR was offset by higher wheat yields after DSR than after PTR in the second year, resulting in similar total system productivity rather than individual crops. AT Delhi, the best variety produced around 4.5 t ha⁻¹ when dry seeded and irrigated at a soil water tension of 20 kPa with about a 10 per cent yield decline when the irrigation threshold tension was increased to 40 kPa (Singh *et al* 2008). Sharma *et al* (2005) reported similar yields (> 6.5 t ha⁻¹) for DSR and PTR. Direct seeding of rice may also allow earlier establishment of the succeeding wheat crop (Giri 1998), reduced methane emissions, and higher profit in areas with an assured water supply

(Balasubramaniam and Hill 2002). Rice is thus very sensitive to reduction in water availability around flowering as this results in spikelet sterility (Ekanayake *et al* 1989).

Direct sowing of rice on June 15 gave 8.8, 37.8 and 46.6 per cent higher grain yield than that sown on July 1, July 15 and August 1, respectively at New Delhi (Narayanaswamy *et al* 1982). Direct sowing on June 1-10 produced higher rice grain yield due to higher number of effective tillers, filled grains, panicles, 1000-grain weight and lesser spikelet sterility as compared to crop sown on 20 June at Ludhiana (Gill *et al* 2006). An experiment was conducted at PAU, Ludhiana reported that higher grain yield was recorded in case of transplanting 25-day old seedlings which was at par with direct sowing of rice on zero and 7 days afternursery sowing. Direct sowing of rice on 14 and 21 days after nursery sowing was inferior to PTR.

The type of cultivar has also been reported to influence the performance of DSR. Gill *et al* (2006) evaluated four rice cultivars (PR 111, PR 115, PR 116 and IR 64) under direct sown conditions at Ludhiana, Punjab. A short duration and early maturing rice variety (PR 115) was superior in terms of grains per panicle, dry matter accumulation, effective tillers, spikelets and grain yield. It was followed by medium and long duration varieties like PR 111, IR 64 and PR 116. Early maturing variety PR 115 was superior to long duration PR 116 under loamy sand and loamy soils at Ludhiana and Ladhowal, respectively (Anonymous 2007).

Singh *et al* (2015) reported that weed competition is one of the major causes of low yield of upland rice reducing yields up to 100 per cent. Manna (1991) reported a yield reduction of 25 per cent in transplanted rice, 32 per cent in puddle broadcast rice and 52 per cent in direct sown upland rice due to weeds. Govindarasu *et al* (1998) reported that loss due to weeds is greater in wet direct seeded rice than in transplanted rice to the extent of 50-60 per cent and even a complete crop failure at many times. Reduction in grain yield due to unchecked weed infestation in transplanted rice has been reported to the extent of 63 per cent (Gopinath and Pandey 2004).

The expected yields in aerobic rice systems (ARS) are somewhat lower than those obtained under lowland flooded conditions, but double or treble of that obtained under upland conditions. However, ARS has been successful in cool temperate regions. For warm humid rice growing regions, a partial aerobic rice system (PARS) may be a more plausible alternative. Saharawat *et al* (2010) and Reddy *et al* (2004) reported similar yield and water application in unpuddled and puddled transplanted rice in farmer participatory trials in Haryana, India. Dry direct-seeding of rice and wheat after no-tillage performed similar to the conventional practice but with significant savings in water and labor use (Bhushan *et al* 2007). The risk of yield loss in DSR due to weeds by all seeding methods was reported to be

higher than for PTR due to suppression effect of standing water on germination and growth of weeds (Rao *et al* 2007).

Singh *et al* (2009) reported that in the first year of their study in Bihar, India, the broad leaf weeds were 144 m⁻² in DSR as compared to 109 m⁻² in PTR. Further, it was reported that Pretilachlor requires stagnation of water for a few days for its full efficiency (Singh *et al* 2009) while this conditional performance favors weed germination and growth under upland conditions.

De Datta *et al* (1981) reported that a water deficit during vegetative phase reduced rice yield by 34 per cent, whereas water deficit during reproductive phase reduced it by 50 per cent. Recent studies in Senegal indicates that the best results (yield cum water saving) were obtained when the rice field was kept flooded during the first half growing season (vegetative phase) and under alternate wetting and drying (AWD) during the second phase (reproductive phase) of the growing period. Maintaining AWD throughout the growth period of rice reduced the grain yield of rice by 20 per cent. The AWD in PTR using field water tube is also gaining ground in Bangladesh (Tuong *et al* 2009).

In aerobic rice experiments at the International Rice Research Institute (IRRI), yields of aerobic rice gradually declined over the time as compared to a continuously flooded control (George *et al* 2002, Peng *et al* 2006). Similar observations were made for DSR in sandy loam soils of Punjab, India (S S Kukal, Personal Communication). Yield declines and even failures in continuous upland rice cultivation are reported from Philippines (Ventura and Watanabe 1978, Ventura *et al* 1984, George *et al* 2002).

In Brazil, the rice yields declined after 2 years of consecutive upland cultivation and after 5 years of monoculture, rice yield was only 1.5 t ha⁻¹ as compared to 4.3 t ha⁻¹ after 3 years of soybean (Fageria and Baligar 2003, Pinheiro *et al* 2006). A fairly large per centage of rice growing soils are Ultisols and Oxisols and are quite acidic. For a major part, flooding overcomes this problem and rice is successfully grown. However, in upland conditions, soil acidity develops and a number of problems crop up, such as, Al-toxicity, phosphate fixation (Kirk *et al* 1998, Prasad and Power 1997) and nutrient deficiencies. Oxisols are notorious for phosphorus immobilization because of their high iron oxide content.

Studies in Indo-Gangetic Plains (IGP) have shown that the performance of DSR can vary from location to location within a country (Bhatt and Kukal 2015). For example, in the north-western IGP, there is a tendency of a yield penalty with DSR (Gathala *et al* 2011, Jat *et al* 2009, Saharawat *et al* 2009), while in eastern regions the reverse is true. A possible reason for this differential performance in northwestern versus eastern IGP is lower annual rainfall in the former (400–750 mm) than in the later (1000–1500 mm) (Gupta and Seth 2007).

Yield in DSR is often lower than PTR principally owing to poor crop stand and higher weed infestation (Singh *et al* 2005, Bhatt and Kukal 2015). For instance, substantially higher grain yield was recorded in DSR (3 t ha⁻¹) than in PTR (2 t ha⁻¹), which was attributed to the increased panicle number, higher 1000-kernel weight and lower sterility per centage (Dingkuhn *et al* 1991, Sarkar *et al* 2003). The DSR in moistened soil produced taller plants, higher dry matter, lower chlorophyll content, specific leaf weight, and more panicles and sterile spikelets than transplanted rice (Sarkar *et al* 2003). However slightly lower yields were obtained with DSR (Balasubramanian *et al* 2003, Gupta *et al* 2004).

Gupta *et al* (2002) reported 10 per cent higher yields in DSR than flooded PTR. Bhushan *et al* (2007) reported similar yields in both treatments in the first year (>7 t ha⁻¹), although yield was achieved in different ways-much higher tiller and panicle density and lower floret fertility in DSR compared with PTR. Yield of DSR was significantly lower than that of PTR in the second year (by 13 per cent). Sharma *et al* (2005) also reported similar yields (>6.5 t ha⁻¹) for DSR and PTR. The yield loss with DSR was offset by higher wheat yields after DSR than after PTR in the second year, resulting in similar total system yield, and again demonstrating the importance of considering the total system rather than individual crop productivity (Bhatt and Kukal 2015).

Sudhir-Yadav *et al* (2010b) observed yields of both DSR and PTR to decline when the soil was allowed to dry to soil matric tension higher than 20 kPa, and yield decline was more rapid than that of PTR as soil matric tension increased to 40 and 70 kPa. On a marginally sodic silt loam at Modipuram, yield of DSR declined significantly (by 15 per cent) as the threshold for irrigation increased from 10 to 20 kPa at 20 cm (Sharma *et al* 2002). The DSR was affected by iron deficiency in the studies of both Sharma *et al* (2002) and Sudhir-Yadav *et al* (2010b), more so as the threshold tension for irrigation increased.

The most damaging soil-borne pathogen for yield decline in aerobic rice is root-knot nematode (RKN) *Meloidogyne graminicola* (MG) (Arayarungsarit 1987). It is incapable of entering the rice roots under flooded conditions although it can survive for extended periods under such conditions (Padgham *et al* 2004) and attacks rice roots when aerobic conditions come up. In a study in Philippines, RKNs were found to be most damaging pathogens for aerobic rice Apo (Kreye *et al* 2009). Such nematodes have been observed as nodules in the roots of DSR in Punjab, India (S S Kukal, Personal Communication).

Flooding of rice after successful establishment can alleviate nutrient deficiencies (i.e., Fe and Zn) and soil-borne diseases (i.e., nematodes). Also in the eastern IGP, current yields of CT-PTR are much lower than that in the northwestern IGP, therefore, it is easier to achieve equivalent yield with DSR.

Weeds are a major constraint to the success of DSR in general and to dry-DSR in particular (WARDA 1996, Balasubramanian and Hill 2002, Johnson and Mortimer 2005, Singh *et al* 2006, Rao *et al* 2007, Singh *et al* 2015 a,b). Research has shown that, in the absence of effective weed control options, yield losses are greater in DSR than in transplanted rice (Baltazar and De Datta 1992, Rao *et al* 2004). Weeds are more severe in DSR than in puddled transplanting because (1) emerging DSR seedlings are less competitive with concurrently emerging weeds and (2) the initial flush of weeds is not controlled by flooding in wet- and dry-DSR (Rao *et al* 2007, Kumar *et al* 2008). However, unchecked weed competition causes yield losses to the tune of 50-65 per cent under wet direct sown summer conditions.

Thus, performance of DSR has been controversial in literature from crop and water productivity as compared to the puddle transplanted system. Its success is location- and site specific apart from depending on the rainfall and weather conditions (Bhatt and Kukal, 2015). Moreover, the land and water productivity of the cropping system involving rice and wheat grown with resource conservation techniques need to be evaluated under different scenarios.

2.2.2 Wheat

2.2.2.1 Zero till wheat

Sustainability of rice-wheat (RW) cropping system has come into question, due to the stagnating or declining yields (Ladha *et al* 2003), degrading soil (Bhandari *et al* 2002), declining ground water tables (Hira *et al* 2004), and polluting air (Bijay-Singh *et al* 2008). More than 90 per cent of the major RW areas in north-west India (Punjab, Haryana, western Uttar Pradesh) is irrigated using underground water, and the rapid decline in groundwater levels is probably the biggest challenge to the sustainability of the RW system (Humphreys *et al* 2010). The majority of the rice and wheat in Punjab is combine-harvested, leaving 0.3–0.6 m high anchored straw and loose straw in windrows. Management of the rice stubble (more than 7 t ha⁻¹) is a major problem as timely sowing of wheat is the first priority for the farmers. Many tillage passes are required for incorporation, coupled with the need to allow time for the straw to decompose sufficiently to avoid N immobilization which delays wheat sowing (Gajri *et al* 2002). Incorporation of the rice straw delays wheat sowing beyond the optimum date (before 15th November) for maximum yield beyond which the wheat yields start decreasing. Thus the farmers opt for burning of crop residues which results in air pollution and loss of nutrients @ 35 kg N ha⁻¹, 21 kg K ha⁻¹ and 3 kg ha⁻¹ each of P and S (Yadvinder-Singh *et al* 2008) coupled with degrading soil physical and biological health (Yadvinder-Singh *et al* 2005). Burning of rice residues is a major source of air pollution in the region, in the forms of green house gas emissions (CO₂, CH₄, NO₂, N₂O) and particulate matter (Gupta *et al* 2004).

Thus, the technologies that enable retention of rice residues over the soil surface would greatly reduce air pollution and improve declining crop and water productivity in the region.

Over the last decade, wheat establishment using the Pantnagar zero till drill has become popular among farmers (Harrington and Hobbs 2009), eliminating tillage and enabling earlier wheat sowing. However, use of this seed drill also requires removal (normally by burning) of at least the loose residues left by the combine harvester. The recent development of a residue/trash handling zero tillage sowing implement, the 'Happy Seeder' (Sidhu *et al* 2007, 2008) provides the capability of direct drilling of wheat seeds in rice residues. The Happy Seeder simultaneously cuts and removes the straw in the way of the sowing tynes, and spreads the straw on the surface as mulch behind the tynes. Therefore, direct drilling of wheat seeds into the soil is a viable option to put wheat seeds into soil and secondly the loose straw acts as mulch, reduces soil evaporation (E_s) and partitions greater fraction of water toward transpiration component (Balwinder Singh *et al* 2011b). The direct drilling of wheat in standing rice stubble is an important resource conservation technique being propagated in the rice-wheat regions of South Asia (Beff *et al* 2013, Balwinder Singh *et al* 2014).

The positive benefits of zero tillage on crop production (Paccard *et al* 2015), water use efficiency (Guan *et al* 2015), carbon sequestration (Zhangliu *et al* 2015) and economic performance (Tripathi *et al* 2013) are well recognized. Retaining the residues as a mulch also offers the potential benefits of reduced water loss due to the suppression of soil evaporation, suppression of weeds, increased soil organic C, and improved soil structure which finally improves the grain yields (Yadvinder-Singh *et al* 2005). Residue mulch can suppress weeds by (a) providing a physical barrier to emerging weeds (Mohler and Callaway 1991, Mohler and Teasdale 1993, Mohler 1996) and (b) releasing allelochemicals in the soil with decomposition (Weston 1996, Chou 1999). Higher soil water content and increased yield of wheat with rice straw mulch have previously been reported from India and Bangladesh (Rahman *et al* 2005, Sidhu *et al* 2007, Balwinder singh *et al* 2014). It is well established that mulch can suppress soil evaporation (E_s) (Al-Darby *et al* 1989, Balwinder singh *et al* 2011b, Kukal *et al* 2014) which could account for 30-60 per cent of total evapo-transpiration (ET) during wheat production (Balwinder singh *et al* 2014, Siddique *et al* 1990). This suggests that reducing E_s may reduce ET and thus result in increased water productivity based on ET (WP_{ET}) by about 10–20 per cent (Deng *et al* 2006). Thus mulching could be beneficial in terms of reducing water loss from the under ground sources, as well as in reducing irrigation requirement (Mandal and Ghosh 1984, Li *et al* 2004).

Thus, higher yields are expected in the ZT plots because of better edaphic environment and water retention but contradictory results are reported in the literature (Singh

et al 2015, Chopra and Chopra 2010), which was because of the higher weed pressure in ZT plots (Balwinder Singh *et al* 2014) because of lesser herbicides efficacy in ZT plots as compared to CT plots (Singh *et al* 2015). On-station and on-farm trials with ZT wheat in the rice–wheat system of the IGP have shown primarily positive impacts on wheat crop management, particularly through reduced input needs combined with potential yield increases (Aslam *et al* 1989, Hobbs and Gupta 2003, Laxmi *et al* 2007, Malik *et al* 2002, 2005). Further Jat *et al* (2014) in their seven year experiment on the clay loam soil reported that higher grain yields and economical advantage of conservation agriculture (CA) was realized after 2-3 years as the adaptation of conservation agriculture based component technologies evolved over the time and the farmers have to settle with somewhat lower yields during the initial years. Thus the farmers need to be convinced about lower crop yields during initial few years for adoption of this technology for better land and input productivity at later stages.

In South Asia, late sown wheat is subject to terminal heat stress whereas timely sown wheat has a correspondingly longer growing period. Wheat crop established before 15 November yielded significantly more (200 kg ha⁻¹) compared to crop established thereafter. The use of ZT allows the wheat crop to be sown sooner than would be possible using conventional methods, which significantly reduces the turnaround time. Thus, there is no significant difference in terms of time of wheat establishment between ZT and conventional plots. This suggests that farmers have generally been reluctant to significantly advance their wheat planting date despite apparently increased opportunities to do so with ZT. This is an important consideration in many parts of the rice-wheat belt, where late planting reduces grain yields as terminal heat reduces wheat yield potential by 1-1.5 per cent per day if planting occurs after 20 November (Ortiz Monasterio *et al* 1994, Mehla *et al* 2000, Hobbs and Gupta 2003).

Chakraborty *et al* (2010) reported that rice straw mulch left because of zero tillage increased the mean wheat grain yield by 17 per cent as compared to the conventional tillage. Further, Gupta *et al* (2010) and Jat *et al* (2009) reported that mulch in wheat helps in reducing the canopy temperature by 2.9°C during grain filling stage to mitigate the terminal heat stress in wheat and thus promotes grain yields. Erenstein and Luxmi (2008) documented that zero till wheat helps in promoting grain yields to the tune of 5-7 per cent mainly due to the timely sowing of wheat crop. It has been observed that the zero tillage technique ameliorates late planting, improves fertilizer and water use efficiency (Yadav *et al* 2005) with the condition of proper weed control.

However, in general the ZT plots suffer due to significantly higher weed biomass as compared to the CT plots, as zero till plots leave of the most weed seeds in the top 1.0 cm of

the soil profile which germinate easily because of better availability of the soil moisture and nutrients (Singh *et al* 2014, Singh *et al* 2015). Divergent tillage systems affected weed biomass significantly. The zero tillage had been reported to increase weed density (Kumar *et al* 2014, Singh *et al*, 2015a, Singh *et al* 2015b) and higher weed dry biomass (Singh *et al* 2015). Changes in tillage practices, however, influence the vertical distribution of weed seeds in the soil (Singh *et al* 2015), and this may affect the relative abundance of weed pressure in the field. Under zero tillage, a large proportion of the weed seed bank remains on or close to the soil surface after crop planting (Singh *et al* 2015), which may promote greater emergence of weed species that require light to germinate. With conventional tillage (CT), however, the seedling emergence depends partly on the effect that tillage has on seed burial as deeply buried seeds may not be able to emerge. The soil disturbance caused by tillage systems places weed seeds at different depths, which differ in availability of moisture, diurnal temperature fluctuation and light exposure, and activity of predators (Singh *et al* 2015). All these micro-environmental attributes have the potential to influence the behavior of weed seed bank. The interaction effects of these treatments suggest that lesser herbicide efficacy in ZT plots as compared to the CT plots lead to higher weed pressure and weed biomass and finally result in lower grain yields in the former plots (Singh *et al* 2015).

Farmers of the Indo-Gangetic plain are rapidly adopting zero tillage for sowing wheat after rice mainly because of the lesser cultivation costs as ZT wheat sowing involves no field preparations. In India and Pakistan, there is an average net benefit of US\$150 per ha through higher yields and lower land preparation costs (Gupta 2002). There is an increase in the yield with zero till technology over conventional tillage and the savings are made through reduced fuel consumption and the machinery uses (Gray *et al* 1996). Economically, zero tillage is superior to the conventional method of sowing because more net returns have been recorded than on conventional wheat farms, in addition to the added bonus of eco-friendly practice (Nagarajan *et al* 2002).

Branct (1989) observed that zero-tillage was superior to conventional tillage resulting in higher yields. Similarly several studies have shown that crops grown under zero tillage have yielded similarly or better than those grown under conventional tillage (Mahli and Nyborg 1990, McAndrew *et al* 1994). Buhler (1992) reported that corn yields were not affected by tillage. However, Vencill and Banks (1994) observed that sorghum grain yields were higher with zero tillage system when it was combined with high degree of weed management than in conventional tillage system.

Crop yield in zero tillage were comparable with conventional tillage only if weeds were controlled properly (Bottenburg *et al* 1997, Singh *et al* 2015). A positive yield effect of ZT is often associated with more timely wheat establishment (Hobbs and Gupta 2003, Laxmi

et al 2007, Mehla *et al* 2000). In Pakistan Punjab, mixed response of farmers regarding wheat yield was obtained with 54 per cent of farmers reporting a yield increase, 30 per cent reporting decrease and 16 per cent reporting no change (Ahmad *et al* 2007). Furthermore, average wheat yields were significantly higher than in the zero tillage in Haryana, India (Erenstein *et al* 2007). This suggests that ZT plots in Haryana were less susceptible to yield loss, contributing to the observed yield advantage over conventional, possibly through better soil-moisture conservation. The overall late sown wheat establishment in Punjab is likely to further contributed to the lack of a yield effect, as the relative performance of zero tillage timely sown wheat (Mehla *et al* 2000, Malik *et al* 2002). On-farm experiments in Pakistan showed that compared to conventional, ZT wheat improved the crop stand and yielded 10–40 per cent higher under different soil types and moisture regimes (Aslam *et al* 1989).

Significantly higher grain yields were obtained with ZT when wheat was sown at the recommended time, i.e. early to mid-November. For the late sown sites, there was no significant yield difference between ZT and conventional tillage planted wheat (Aslam *et al* 1989). The lack of a significant yield effect has undermined widespread ZT acceptance in Punjab (Farooq *et al* 2007). Without a yield benefit, the immediate payoff to ZT is reduced to its cost-saving potential as no field preparation is involved here. Adoption of zero tillage in IGP has been rapid since mid-1990s, increasing to over 3 million ha by 2006 (Harrington and Hobbs 2009). The major driver for adoption is increased profitability as a result of lower establishment costs (Erenstein and Lakshmi 2008).

The extension services in Pakistan Punjab have discredited ZT for the risk in pest carryover in the rice stubble (particularly rice stem borer). There is however, no scientific evidence of such risk (Inayatullah *et al* 1989, Srivastava *et al* 2005). Aslam *et al* (1993) have shown that zero-tillage establishment of wheat after rice gives equal or even better yields than when wheat is conventionally sown. The extra yield is associated with timely planting. Further studies in various institutions in South Asia with zero-tillage establishment of wheat on several different soil types using different methods suited to different socioeconomic conditions also confirm that tillage can be reduced when establishing the wheat crop after rice (Hobbs *et al* 1997) provided timely and effective weed control is there.

Contrary to the beneficial effects of zero tillage, Tahir *et al* (2008) reported a 6.8 per cent lower wheat yields in ZT plots than CT plots. They further reported higher weed biomass (1.6 t ha^{-1}) as compared to the CT plots (0.5 t ha^{-1}) at 35–40 days after transplanting. Similar results were also reported by Malhi *et al* (1988), De vita *et al* (2007), Ordonez Fernandez *et al* (2007), Chopra and Chopra (2010) and Singh *et al* (2015). Thus, there is a need to carry out the residual effect of zero tillage in wheat on the next rice crop including the intervening period in between two crops (Bhatt and Kukal 2015).

2.2.3 Rice-wheat system:

As said above the productivity of individual crops under conservation tillage techniques may not be a true indicator of benefits, until it is observed from the perspective of the cropping system as a whole. Jat *et al* (2014) reported in their 7 year experiment that during the initial three years higher rice grain yield was recorded in conventional tillage (CT) based rice systems (CTR–CTW and CTR–ZTW) than in conservation agriculture (CA) based systems (ZTDSR–ZTW, UpTPR–ZTW). During the fourth and fifth years, the rice yields under CT and CA were comparable whereas sixth year onwards, higher yields were recorded under CA-based than in CT-based systems. However, the wheat yield was higher in CA based system right from the second year onwards. They observed the lowest wheat yield in the system where preceding rice crop was grown with intensive tillage operations (CTR). The RW system productivity was higher in almost all the CA-based than in the CT-based and mixture of CT- and CA-based systems from the second year onwards. The net returns were always higher in CA based than in CT-based system although the significant differences were obvious only from fourth year onwards in rice and second year onwards in wheat as well as at the system level. The higher grain yields and economical advantage of CA was realized after 2–3 years as the adaptation of CA-based component technologies evolved over the time. In medium term, they observed that CA-based systems to be agronomically and economically superior to CT-based systems for rice–wheat rotation in a small holder production system of eastern IGP of South Asia. Hence, CA-based RW production system is one of the pathways for improving productivity, income and food security while sustaining the natural resources in smallholder production system of eastern IGP.

The total rice–wheat system grain yield ranged from 5.07 to 13.1 Mg ha⁻¹ across various treatments and years. During first year, the highest system productivity was recorded under CTR–CTW followed by CTR–ZTW, and ZTDSR–ZTW + R (Jat *et al* 2014). Thereafter, the system productivity was consistently higher in CA-based systems (e.g. ZTDSR–ZTW + R) than other systems. ZTDSR–ZTW yielded at par with ZTDSR–ZTW + R in all years except in first year and the last two years when the yield was lower in ZTDSR–ZTW system. The system productivity of unpuddled transplanted rice followed by zero tilled wheat (UpPTR–ZTW) was lower in the initial three years but it turned out to be one of the higher producing systems from fourth year onwards with average yearly increment of 1.06 Mg ha⁻¹. The system productivity of direct seeded rice followed by wheat both on permanent raised beds (PBDSR–PBW) was lower during the initial four years of the experimentation but recorded the second highest in succeeding years. The system productivity was lower during almost all the years of experimentation in the system where at least one of the crops involved intensive tillage, i.e. in CTR–CTW, CTR–ZTW and ZTDSR–CTW systems (Jat *et al* 2014).

The above studies indicate that the impact of rice or wheat established through different techniques, on the preceeding or succeeding crops need to be studied for realistic land and water productivity of the whole cropping system including the intervening period in between.

2.3 Impact of crop establishment and conservation tillage techniques on irrigation water use and irrigation water productivity

2.3.1 Rice

2.3.1.1 Mechanical transplanting

The effect of tillage and establishment method on water productivity also appears to be variable. Many studies in South Asia (Hobbs *et al* 2002, Sudhir-Yadav *et al* 2011a) observed similar or higher yield of DSR than PTR under well-watered conditions. Establishment methods which involve puddling have several disadvantages, including higher tillage costs, adverse effects on soil structure for upland crops grown in rotation with rice (So and Ringrose-Voase 2000) and high water requirement for crop establishment. The reported amount of irrigation water required for puddling varies from 100 mm (Sudhir-Yadav *et al* 2011b) to 544 mm (Bhuiyan *et al* 1995). Water input for crop establishment can be reduced by avoiding puddling, with or without a change in the crop establishment method. For example, both mechanical transplanting and wet seeding can be done in non-puddled soil after saturating the soil (after dry tillage or no tillage) (Balasubramanian and Hill 2002, Malik *et al* 2011). Mechanical transplanting could potentially solve the declining water availability in general and labour scarcity problem in particular. However, to date attempts to mechanize transplanting in puddled fields have not been successful in north-west India. However, mechanized transplanting in non-puddled fields is a promising new technology and would help solve the problem of labor and water shortage. Mechanical transplanting into non-cultivated soil (zero till transplanting) has recently been shown to be a very promising technology for improving the water productivity in north-west India, with major benefits including large savings in energy and labor, and regular plant spacing (Sharma *et al* 2005, Malik and Yadav 2008).

Mechanical transplanted seedlings established in the field around a month later as compared to the direct seeded rice. Hence 8-10 general irrigations which are applied to DSR crop can be saved in MTR which might be responsible for the recorded higher irrigation water productivity in MTR plots despite of lower grain yields in the DSR plots (S S Kukal, Personal Communication). Bhatt and Kukal (2014) reported that irrigation water productivity (WP_i) of MTR plots was significantly higher than that of DSR plots but similar to the PTR plots, being lower in MTR-ZT plots. The higher WP_i of MTR-P than MTR-ZT plots was due to lower

grain yield in MTR-ZT plots, which was further due to higher weed biomass in MTR-ZT plots.

Mechanical transplanting in dry cultivated (Singh *et al* 2005, Duraisamy *et al* 2011) or in uncultivated soils is being advocated as a good option (Malik and Yadav 2008, Sharma *et al* 2005) for improving the declining water productivities in the region. There are few reports comparing the water use in the puddle and unpuddled transplanted rice.

Very few studies related to detailed water balance characterization under conventional PTR and mechanically transplanted rice (MTR) are reported in the literature, particularly in coarse and medium textured soils. Moreover, increased irrigation water productivity of MTR could impact the irrigation water productivity of following wheat crop. This needs to be studied in detail for the rice-wheat system as a whole. Thus, the water balance studies in rice-wheat cropping system as a whole including the intervening period need to be carried out under different establishment methods viz. conventional PTR and MTR under tilled and zero-tilled conditions.

2.3.1.2 Direct seeded rice

With increasing constraints of water availability, there has been considerable interest in expanding the aerobic cultivation practices employed in upland rice to lowland environments, where anaerobic, paddy cultivation is traditional, particularly in the NW India and Punjab in Pakistan (Huaqi *et al* 2003, Bouman *et al* 2005). The aerobic rice technology eliminates puddling and flooding, and presents an alternative system in reducing water use and increase water productivity. Aerobic rice saved 73 per cent of irrigation water for land preparation and 56 per cent during the crop growth period (Castaneda *et al* 2003). Main driving force behind direct seeding of rice is the economic water use as it avoids puddling operations and rice seeds are directly placed in the tilled/untilled soil. A fundamental approach to reduce water inputs in rice is growing like an irrigated upland crop, such as wheat or maize. Instead of trying to reduce water input in lowland paddy fields, the concept of having the field flooded or saturated is abandoned altogether (Bouman and Tuong 2001). Case studies showed that yields and the water use was about 60 per cent lower than that of lowland rice, total water productivity 1.6-1.9 times higher, and net returns to water use was twofold higher. Aerobic rice requires lesser labor and irrigation water than lowland rice and can be highly mechanized (Huaqi *et al* 2003).

Input water savings of 35–57 per cent have been reported for dry seeded rice (DSR) sown into non-puddled soil with the soil kept near saturation or field capacity compared with continuously flooded (5 cm) transplanted rice (Sharma *et al* 2003, Singh *et al* 2003). However, yields were reduced by similar amounts due to iron or zinc deficiency and increased incidence of nematodes. Contrary to the results of small plot replicated

experiments, participatory trials in farmers' fields in India and Pakistan suggest a small increase or 10 per cent decline in yield of DSR on the flat compared with puddled transplanted rice and around 20 per cent reduction in irrigation time or water use (Gupta *et al* 2003). In their experiments on a high-yielding lowland rice variety (IR20) like an upland crop under furrow irrigation, De Datta *et al* (1973) reported that total water savings were 56 per cent and irrigation water savings 78 per cent compared with growing the crop under flooded conditions.

The water use efficiency of the aerobic varieties under aerobic conditions was 164–188 per cent higher than that of a lowland cultivated rice variety. Aerobic rice maximizes water use in terms of yield and is a suitable crop for water-limiting conditions (Xiaoguang *et al* 2003). According to Castaneda *et al* (2003), water use decreased relatively more than yield, and water productivity under aerobic cultivation increased by 20–40 per cent (in one case even 80 per cent) over that under flooded conditions. According to Sudhir Yadav *et al* (2014) dry seeding and transplanting into dry tilled soil had significantly lower total irrigation input (by about 10 per cent) than all other establishment methods. Puddling increased total irrigation input to both transplanted and wet seeded rice in comparison with dry tillage, mainly because of the large amount of water required for soil soaking/puddling. Irrigation input to direct (wet) seeded rice in puddled soil was much higher than for any other establishment method because of both the longer duration in the field and the water requirement for puddling, which resulted in lower irrigation and input water productivity.

Although the overall trend is a savings in irrigation water application with DSR, some studies (Bhuiyan *et al* 1995, Hukkeri and Sharma 1980) have reported higher irrigation water use which could be due to (1) a longer crop growth period in the main field in DSR than in PTR (Rashid *et al* 2009) and (2) higher percolation losses in DSR (Sudhir-Yadav *et al* 2011b). Rainfall pattern and time of occurrence are other major deciding factors in irrigation water use and resulting savings under dry seeding of rice (Bhushan *et al* 2007, Saharawat *et al* 2010). The average water productivity of rice has been reported to be higher in DSR than PTR (Sudhir-Yadav *et al* 2011b, Humphreys *et al* 2010). Bouman and Tuong (2001) observed that most of the water saving technologies, including DSR, results in some yield losses. Therefore, water productivity is a better indicator for making a comparison of different technologies in terms of their effective use of irrigation water and grain production (Tuong 1999).

Further, water usage of DSR is directly related with the clay content as in sandy loam soils, success of DSR is still in question but in clay rich soils of Bihar or Nepal, DSR proves to be a great success (Bhatt and Kukal 2015) because greater clay content of soil capable of

retaining moisture for a longer period of time as compared to the sandy loam soils of the north India which further resulted in higher water use efficiency.

According to Gathala *et al* (2014) zero-tillage direct-seeded rice (ZT-DSR) with residue retention and best management practices provided equivalent or higher yield and 30–50 per cent lower irrigation water use than those of farmer-managed puddled transplanted rice (CT-TPR).

Recently, Kumar and Ladha (2011) based on the published meta-analysis of data from 44 studies from different countries in SA, showed an average of 21–25 per cent irrigation water saving with dry direct-seeded rice (DSR) compared with puddle transplanted rice (PTR), generally producing similar or 20–30 per cent lower yields. However, Pathak *et al* (2013) reported that DSR saved 3–4 irrigations compared to the transplanted rice without any yield penalty. Gathala *et al* (2011) reported that DSR used 191 mm (averaged over 7 years) of lower irrigation water (IW) than conventional PTR. Other studies from NW India also showed a 30–33 per cent irrigation savings with DSR compared with PTR, mainly because the PTR was continuously flooded for 2 weeks after transplanting (Sudhir-Yadav *et al* 2011b, Gathala *et al* 2013).

Bouman *et al* (2005) reported that DSR required 190 mm less water for land preparation and had 250–300 mm less seepage and percolation losses than a PTR transplanted rice field. Deeper root growth of DSR crop can also provide better tolerance to water and heat stress. Sudhir-Yadav *et al* (2011b) concluded that there was no difference in ET requirement of PTR and DSR crops and most of the irrigation water reduction was due to reduction in seepage and deep drainage. Moreover, most of the studies except Sudhir-Yadav *et al* (2011b) rely on number of irrigations while calculating IW use in PTR and DSR, which could not give a real picture of IW use as the infiltration rate of puddled soil being one-third of that in unpuddled (DSR) sandy loam soil (Kukul *et al* 2009). Thus, the amount of IW per irrigation is higher in DSR than in PTR fields. This may be truer in coarse- and medium-textured soils than in fine-textured soils. The DSR is an attractive option to the traditional rice production system. It is suggested that the DSR system could be an option for farmers in rainfed lowlands with a limited or an erratic distribution of rainfall (Bouman *et al* 2005, Altin *et al* 2006).

The DSR on raised beds decreased water use by 12–60 per cent, and increased yield by 10 per cent as compared to PTR, in trials at both experimental stations and on-farm (Gupta *et al* 2002). Water productivity in DSR was 0.35 and 0.76 as compared to 0.31 and 0.57 under PTR during 2002 and 2003, respectively, indicating better water-use efficiency (Gill *et al* 2006). In DSR, crop established after applying pre-sowing irrigation, first irrigation can be applied 7–10 days after sowing depending on the soil type. When DSR crop is established in

zero tilled (ZT) conditions followed by irrigation, subsequent 1-2 irrigations are required at interval of 3-5 days during crop establishment phase. Subsequent irrigations at interval of 5-7 days need to be applied in DSR crop. During active tillering phase *i.e.* 30-45 days after sowing (DAS) and reproductive phase (panicle emergence to grain filling stage) optimum moisture (irrigation at 2-3 days interval) is required to be maintained to harvest optimum yields from DSR crop. In a 6-year study conducted in Modipuram on sandy-loam soil, it was observed that dry-DSR can be irrigated safely at the appearance of soil hairline cracks (Gathala *et al* 2011).

Drill seeding of rice and wheat on reduced-till flat land (RT-DSR/RT-DSW) or on raised beds (Bed-DSR/Bed-DSW) saved irrigation or total water use by 62 to 532 mm ha⁻¹, but was less productive than conventional practices; yield loss was high in narrow raised bed-planted crops (Naresh *et al* 2013). Although total productivity was less in zero-till drill-seeded rice and wheat (ZT DSR/ZTDSW: by 1.08 to 1.3 t ha⁻¹), water savings were high because of lower irrigation water need. These results are consistent with previous studies (Ladha *et al* 2009). This suggests a need for further research to perfect double zero-tillage systems and promising options irrigation. Dry direct seeding and zero-tillage rice-wheat system had a savings in labor, input use water requirement and machine use. Conventional practice of puddled transplanting could be replaced by unpuddled and zero-till-based crop establishment methods to save water and labor and achieve higher income (Naresh *et al* 2013).

Singh *et al* (2002) compared the water use and yield of wet seeded rice with and without puddling on a sandy loam at Delhi, with water depth maintained at 5 cm in both treatments. They observed that there was an irrigation water saving of only 75 mm with puddling, out of a total irrigation water application of 1,537 mm compared to that in without puddling. Thus, even on this highly permeable soil, the irrigation water saving with puddling was relatively small in comparison with the total water use. However, detailed studies in relation to water balance parameters of DSR in comparison to puddled transplanted rice (PTR) need to be carried out for better irrigation water management.

2.3.2 Wheat

2.3.2.1 Zero tillage

Zero tillage (ZT) has been evaluated in wheat in RW system because of wet soil conditions after rice and long time (10–15 days) needed for seed bed preparation resulting in poor wheat yields. Several studies (Hobbs *et al* 2000, Gupta *et al* 2002, Hobbs and Gupta 2003b) showed 15–30 per cent savings in irrigation water under ZT wheat compared to conventionally till in the rice-wheat belt of the Indo-Gangetic plains of South Asia. Because ZT takes immediate advantage of residual moisture from the previous rice crop, as well as

cutting down on subsequent irrigation requirements, IW use is reduced by about 10 cm (Malik *et al* 2002).

He *et al* (2009) conducted a 2-year no-tillage experiment and established that zero tillage increased crop yields by 6.7–8.9 per cent and water use efficiency by over 6.0 per cent compared to conventional ploughing in Dingxing, Hebei province. Results from other studies also reported that zero-tillage systems were effective in improving soil moisture and increasing crops yields in North China Plain (Zhou *et al* 2007, Jin *et al* 2008). Studies conducted on research farms however, showed insignificant differences in irrigation input between ZT and conventional methods compared with what farmers usually report and what other studies have presented (IWMI Primary surveys in Pakistan Punjab, Ahmad *et al* 2007, Hobbs and Gupta 2003a). It is possible that more timely sowing of the conventional wheat at the same time as the ZT allowed better use of conserved soil moisture for the wheat, which does not normally occur in field conditions when conventional sowing is delayed. Using ZT for wheat in the RW system in the IGP can save 1 million l of irrigation water and 98 l of diesel per hectare of land (Reeves *et al* 2001, Pathak *et al* 2009).

Studies in Haryana (Erenstein *et al* 2008) showed that WP_1 was significantly (17 per cent) higher in ZTW than with conventional tillage, due to slightly higher yields (by 4 per cent) and slightly lower irrigation amount (by 9 per cent), although the average number of irrigations for both establishment methods was the same. Zero till sowing has already been reported to reduce the amount of irrigation water needed for wheat in north-west India (Erenstein and Laxmi 2008, Erenstein *et al* 2008). Balwinder-Singh *et al* (2011a) reported that rice straw mulch @ 8 t ha⁻¹ in ZT wheat in the IGP of India reduced evaporation by 42–48 mm during wheat growing season. Furthermore, Happy Seeder may allow direct seeding of wheat in rice fields using residual soil moisture without the need for pre-sowing irrigation (PSI) (about 75–80 mm), because residual soil moisture after rice gets lost during the seed bed preparation under conventional tillage. Studies have demonstrated that mulching in wheat has a significant positive effect on soil water conservation in reduced and no tillage systems and the effect was more pronounced in dry periods (Bijay-Singh *et al* 2008, Sidhu *et al* 2010, Verhulst *et al* 2011). Chakraborty *et al* (2010) demonstrated that rice straw mulch reduced crop water use by 3–5 per cent, and improved water use efficiency by 38.3 per cent compared with no mulch. From a field study conducted in Indian Punjab, Ram *et al* (2013) reported that wheat yields were similar when it received three irrigations under rice straw mulch and four irrigations with no mulch, thereby saving one irrigation (75 mm) and increasing WUE. From a simulation study using long-term weather data of NW India, Balwinder-Singh *et al* (2011b) predicted that, with mulch in ZT wheat, one irrigation would be saved in about 50 per cent of the years. Thus, zero till (+mulch) wheat really helps in saving of irrigation water and in improving the irrigation water productivity of the region.

2.3.3 Rice-wheat system

According to Naresh *et al* (2013) in the farmer's participatory trials were conducted in the north west India for 3 years to evaluate various tillage and crop establishment systems for their efficiency in labor and water, and economic profitability in the wheat-rice cropping systems. Yields of rice in conventional puddled transplanting were higher as compared to, unpuddled transplanting, reduced-till transplanting, and direct-seeding systems. Yields of wheat following both conventional or alternative tillage and crop establishment were also equal.

2.4 Impact of crop establishment and conservation tillage techniques on soil physical environment

2.4.1 Rice

2.4.1.1 Mechanical transplanting

A field trial was conducted for four years at Modipuram by Gangwar and Singh (2010) to assess the effect of rice crop establishment methods on the productivity and physical health of the soil and they observed that infiltration rate and bulk density of the soil were not influenced by mechanical transplanting when compared with the manual transplanting of rice.

2.4.1.2 Direct seeded rice

Soil sickness is the major disadvantage of aerobic rice cultivation reported by many researchers throughout the globe in texturally divergent soils and which is a main challenge ahead of sustainable agriculture. Ventura and Watanabe (1978) and Ventura *et al* (1984) reported that for continuously grown upland rice in Philippines, yield reductions of 30–60 per cent as well as yield failures and rapid yield loss in repeated cropping of aerobic rice. Such a yield decline may be associated with autotoxicity (allelopathy) as assumed for Brazil (Pinheiro *et al* 2006), or the phenomenon of “soil sickness”, which comprises the potentially interwoven effects of allelopathy, nutrient depletion, build up of soil-borne pests and diseases and soil structural degradation (Ventura and Watanabe 1978). Maintaining soil health is of prime importance thus by adopting certain measures like application of farm yard manures, practising green manuring during intervening periods, alternative wet-direct seeded rice and dry-direct seeded rice are some important management techniques for maintaining the soil health.

As per Gathala *et al* (2010) after seven-year of rice-wheat rotation on medium textured soil bulk density (D_b) of the 10- to 20-cm soil layer was highest under puddled treatments (1.74–1.77 Mg m^{-3}) and lowest under ZT treatments (1.66–1.71 Mg m^{-3}). Likewise, soil penetration resistance (SPR) was highest at the 20-cm depth in puddled treatments (3.46–3.72 MPa) and lowest in ZT treatments (2.51–2.82 MPa). Compared with conventional practice,

on average, water-stable aggregates (WSA > 0.25 mm) were 28 per cent higher in ZT direct-seeding with positive time trend of 4.02 per cent yr⁻¹. Infiltration was higher (0.29–0.40 cm h⁻¹) in ZT treatments than puddled treatments (0.18 cm h⁻¹). The least-limiting water range was about double in ZT direct-seeding than that of conventional practice. Gradual improvement in soil physical parameters in ZT system resulted in improvement in wheat yield and is expected to be superior in long-run on system (rice+wheat) basis.

2.4.2 Wheat

2.4.2.1 Zero tillage

Resource-conserving technologies (RCTs) such as zero-tillage (ZT) have been shown to be beneficial in terms of improving soil health, water use, crop productivity and farmers' income (Gupta and Sayre 2007, Gupta and Seth 2007). Zero tillage (ZT) improves the soil physical environment (Kumar and Goh 2000, Bhaduri *et al* 2014, Paccard *et al* 2015) because of residue retention on the fields resulting in increased infiltration rate, water retention, hydraulic conductivity, lower soil compaction (Palese *et al* 2014, Bhaduri *et al* 2014, Zheng *et al* 2015) etc while conventional tillage break macro-aggregates into the micro-aggregates which adversely affect the soil properties (Roper *et al* 2013, Das *et al* 2014, Kuotsu *et al*, 2014).

Jat *et al* (2009) showed improvement in physical properties of the soil which was under double zero tillage for the two years. They further showed that the CT system had higher bulk density and penetration resistance in 10–15 and 15–20 cm soil layers due to compaction caused by the repeated wet tillage in rice. The steady-state infiltration rate and soil aggregation (>0.25 mm) were higher under permanent beds and double ZT and lower in the CT system. Under CT, soil aggregation was static across seasons, whereas it improved under double no-till and permanent beds. Similarly, mean weight diameter of aggregates was higher under double ZT and permanent beds and increased over time. Thus, double zero till technology ultimately improved the soil physical environment but 3–4 years are required for these technologies to be beneficial at the farmers field (Jat *et al* 2014).

Jin *et al* (2008) reported in their 11 year study that zero tilled plots had mean percentage of macroaggregates (>0.25 mm, +8.1 per cent) and macroporosity (>60 mm, +43.3 per cent) enhanced statistically ($P < 0.05$) in the 0–30 cm soil layer. They further reported that macro- and meso-porosity were greater in no-till soils but micro-porosity was less than that in ploughing soils. In the 0–10 cm soil layer, macroporosity and mesoporosity on ZT plots were 51.2 per cent (significant at $P < 0.05$ level) and 4.6 per cent greater, but microporosity was 3.8 per cent less than on CT plots. In deeper soil layers, ZT treatment also had 61.6 per cent statistically ($P < 0.05$) higher macroporosity in the 10–20 cm soil layer, and significantly ($P < 0.05$) greater (17.8 per cent) mesoporosity in the 20–30 cm soil layer, but mean microporosity

in the 10–30 cm soil layer was 18.3 per cent less. Consequently, mean total porosity was 9.0 per cent greater in ZT (47.9 per cent) than that in CT (43.9 per cent) largely due to an increase in macroporosity and mesoporosity on the NT plots. The percentages of water-stable aggregates of the largest size class (>2 mm) in 0–10, 10–20 and 20–30 cm soil layers for NT were 46.7 per cent, 33.2 per cent and 27.3 per cent significantly ($P < 0.05$) greater than for CT, respectively. Furthermore, no tillage was also associated with a significant improvement in water-stable aggregates of the large size class (2–1 mm) as compared to conventional tillage in the top 2 soil layers (0–10 and 10–20 cm). In the long term, conventional tillage tends to increase soil bulk density, reduce both macroporosity and macro-aggregates, resulting in less water and nutrient availability (Qin *et al* 2006). Numerous researchers have demonstrated that conservation tillage is effective in improving soil physical and chemical properties (Peixoto *et al* 2006, Madejon *et al* 2009). Zhou *et al* (2011) demonstrated that zero-tillage increased the aggregation and stability of soil aggregates in the upper layer (0–10 cm) compared to rotary tillage and conventional tillage after 4 years in Luancheng, Hebei province.

As per John and Singh (2007), bulk density in both the soil layer (0–8 cm and 8–16 cm) was highest in zero tillage treatment and lowest in conventional tillage due to natural soil consolidation and minimum disturbance of soil by tillage operation in zero tillage. According to the results of many investigations, soil hydraulic conductivity, bulk density and compaction increased and porosity decreased because of the application of a zero tillage system (Strudley *et al* 2008). Results from soil aggregation studies on four Indiana soils by Mannering *et al* (1975) showed that as tillage intensity increased, soil aggregation decreased. Aggregation was highest in the 0–5 cm layer of zero tillage treated soil. Zero tilled plots have better aggregate stability (Ghuman and Sur 2001), increased porosity (Francis and Knight 1993) that may facilitate root growth (Martino and Shaykewich 1994) and promoted infiltration while intensive tillage in conventional systems leads to gradual decline in soil organic matter through accelerated oxidation, with a consequent reduction in the capacity of the soil to regulate water and nutrient supplies to plants (Ghosh *et al* 2010). Water infiltration increases with increasing amounts of residue on the surface (Lang and Mallett 1984). Surface residues, as with conservation tillage systems, reduce runoff (1.2 and 2.2 per cent) and increase infiltration than in ploughed soil (8.3 and 21.5 per cent) at 1 and 15 per cent slope respectively (Rockwood and Lal 1974). Lindstrom *et al* (1984) stated that, no till treatment is characterized by higher bulk density, greater penetrometer resistance, lower volume of macropores and reduced infiltration rate. They also observed detachment of soil particles from raindrop impact and subsequent soil crusting at a slower rate on zero tillage surface than on the tilled surface reducing the infiltration rate. Subbulakshmi (2007) stated that soil crusting

at a slower rate on zero-till surface than on the tilled reducing the infiltration rate. Conservation tillage practices viz. zero tillage whereby residues from the previous crop are left on the surface, promotes soil physico-chemical properties, in situ conservation of rainwater, reduces soil evaporation, moderates soil temperature, improves crop productivity and soil quality (Rockström *et al* 2009).

2.4.3 Rice-wheat system

Repeated puddling of coarse-and medium-textured soils has lead to the sub-surface compaction (Sur *et al* 1981, Kukal and Aggarwal 2003a) which has been proving detrimental for the upland crops like wheat (Kukal and Aggarwal 2003b, Singh *et al* 2014). The high bulk density layer at 15-20 cm depth formed due to repeated puddling restricts the root growth of wheat in addition to creating aeration stress (Aggarwal *et al* 1995, Kukal and Aggarwal 2003b). This decrease in wheat yield may be due to the reduction in root growth and distribution in a poor soil physical environment (Hassan and Gregory 1999, Ishaq *et al* 2003, Kukal and Aggarwal 2003b). The destruction of soil aggregates by puddling leads to the formation of surface crusts and cracks on drying, delaying preparation of a seedbed for ensuing crops. When broken by tillage, the resulting large clods provide poor contact with seed, thereby restricting germination of succeeding upland crop.

The reviewed literature shows that various RCTs viz. mechanical transplanting of rice, direct seeding of rice and zero tilled wheat both in rice and wheat have been studied in isolation with respect to crop performance, water productivity and soil physical health improvement while the intervening periods is generally ignored. Further, the system approach regarding residual effect of one RCT in one crop on succeeding or proceeding crop is also missing as the RCTs in one crop may increase the yield potential in the succeeding crop grown conventionally. Thus, the crop performance and soil water balance studies need to be carried out on the basis of complete cropping system as a whole including the intervening period (Jat *et al* 2014, Devkota *et al* 2015). Site-specific packages of resource conservation technologies should be developed for different rice-wheat production systems across the continents keeping under consideration divergent agro-climatic conditions. Because nutrient dynamics particularly of micronutrients are altogether different under water-saving rice production systems, future research should also include the crop nutrition with particular reference to micronutrients. Integrated tools should be developed for weed management in different systems as weeds have the potential to reverse the trends if not controlled. Thus, further studies comparing the performance of different RCTs in wheat-rice cropping system as a whole including intervening period need to be carried out in Indo-Gangetic plains under texturally divergent soils under different agro-climatic regions for recognizing a particular set of RCTs for RWCS for improving sustainability and profitability of the system in the region.

CHAPTER III

MATERIAL AND METHODS

The field experiments were conducted during 2012-14 to study “**Soil water dynamics and water productivity of rice-wheat system under different establishment methods**” at the Soil Science research farm of Punjab Agricultural University, Ludhiana, India.

3.1 LOCATION AND CLIMATE

Ludhiana is situated in the central plain region of Punjab in Trans-Gangetic Zone of India at 30°54'N latitude and 75°98'E longitude with altitude of 247 m above the mean sea level. The climate of the region is subtropical and semi-arid with very hot and dry summers (April-June), wet monsoon season (late June to mid-September) and a cool dry winter (October-February). The mean minimum and maximum temperatures show considerable fluctuations during summer and winter months. Maximum average air temperature above 38°C is common during summers and frequent frosty spells are experienced in December-January. The average annual rainfall is 650-700 mm and a greater portion (about 75 per cent) of this rain is received during summer monsoon from July to September, while in winter a few showers of cyclonic rains are received between December-January and late spring season. The depth to the ground water at the site is around 24 m and the quality of water is good for irrigation purposes.

3.2 EXPERIMENTAL SOIL CHARACTERISTICS

The experimental site was under puddle transplanted rice for the last 20 years except that the field was under direct dry-seeded rice (DSR-CT) sown under tilled conditions during the immediate previous year (2012). Soil samples were taken from randomly selected sites in the experimental field from 0-15, 15-30, 30-60, 60-90 and 90-120 cm soil layers before planting the experimental crop and composite soil samples were obtained by mixing them layer wise. The samples were dried in shade, ground and sieved through 2 mm sieve and analyzed for physico-chemical properties (Table 3.1). The experimental soil was sandy loam (sand 65-69 per cent, clay 11.3-12.7 per cent), neutral to slightly alkaline, non-saline and medium in soil organic carbon (0.44 per cent) in the surface layer. The soil had sub-surface compact layer (bulk density of 1.74 Mg m⁻³ in 15-30 cm layer). The available nutrients were in the medium range while moisture content (per cent w/w) on an average decreased to 71.5 per cent from field capacity to permanent wilting point.

Table 3.1 Basic physico-chemical properties of the studied site

Depth (cm)	Sand (%)	Clay (%)	pH (2:1)	EC (2:1)	O.C (%)	Available nutrients (kg ha ⁻¹)			Db (Mg m ⁻³)	Moisture content (per cent w/w)	
						N	P	K		At 0.3 bar	At 15 bars
0-15	64.7	11.3	7.26	0.25	0.45	341.2	15.2	250.8	1.66	11.3	7.7
15-30	65.9	11.3	7.23	0.31	0.44	332.8	14.2	218.6	1.74	10.4	6.2
30-60	66.8	12.6	7.31	0.32	0.35	--	--	--	1.59	12.1	6.4
60-90	67.6	12.7	7.18	0.26	0.37	--	--	--	1.63	11.3	6.7
90-120	68.2	12.3	7.01	0.34	0.34	--	--	--	1.57	12.1	7.3
120-150	68.8	11.9	7.08	0.33	0.32	--	--	--	1.61	12.5	6.6

3.3 WEATHER DURING THE STUDY PERIOD

Daily maximum and minimum temperature and pan evaporation were measured at the PAU meteorological station, about 1.5 km from the experimental site. Rainfall was measured using an automatic rain gauge at the experimental site. The maximum temperature during March-May was slightly higher in 2012-13 than in 2013-14 and the long-term average maximum temperature. It reversed during June-October being lower in 2012-13 than in 2013-14 and long term average particularly in the months of September and October. However, the minimum temperature was almost similar during 2012-13 and 2013-14, being slightly higher than the long term average during June-July and October (Fig. 3.1a). The pan evaporation in general was lower during both the years of study especially in 2013-14. However, it was higher during June-September in 2013-14 than in 2012-13 and long term average (Fig. 3.1b). The total amount of rainfall was higher (891.6 mm) in 2012-13 than in 2013-14 (582.3 mm) (Fig. 3.1c). However, the rains were better distributed during 2013-14 (42 rainy days) than during 2012-13 (31 rainy days). The month of June recorded abnormally higher rainfall (296.4 mm) during 2012-13 compared to 30.3 mm during 2013-14 (Fig. 3.1d).

3.3.2 Irrigation water quality

The depth to the ground water at the site was around 24 m and the quality of water was good for all crops (Table 3.2).

Table 3.2 Quality of irrigation water used at the experimental site

Replications	Ca ²⁺ +Mg ²⁺ (meq/l)	Cl ⁻ (meq/l)	Residual NaHCO ³	EC (dsm ⁻¹)	CO ₃ ²⁻ (meq/l)	HCO ³⁻ (meq/l)
R1	3.5	0.7	0.0	0.47	0.0	3.5
R2	3.7	0.8	0.0	0.49	0.0	4.0
R3	3.5	0.9	0.0	0.53	0.0	3.7

3.4 EXPERIMENTAL DETAILS

3.4.1 Treatment

The laser leveled field was laid out as per the treatments with wheat grown conventionally (CTW) and with zero tillage (ZTW) with straw load of 4.4 t ha⁻¹ retention at the surface (Fig. 3.2). After wheat harvest, the main plots were split into two sub-plots to impose different sub-plot treatments viz. direct seeded rice (DSR) and mechanically transplanted rice (MTR). The sub-plots were further split into three sub-sub plots for allocating the sub-sub plot treatments of tillage in rice viz. puddling (P), conventionally tillage (CT) and zero tillage (ZT) (Fig. 3.3).

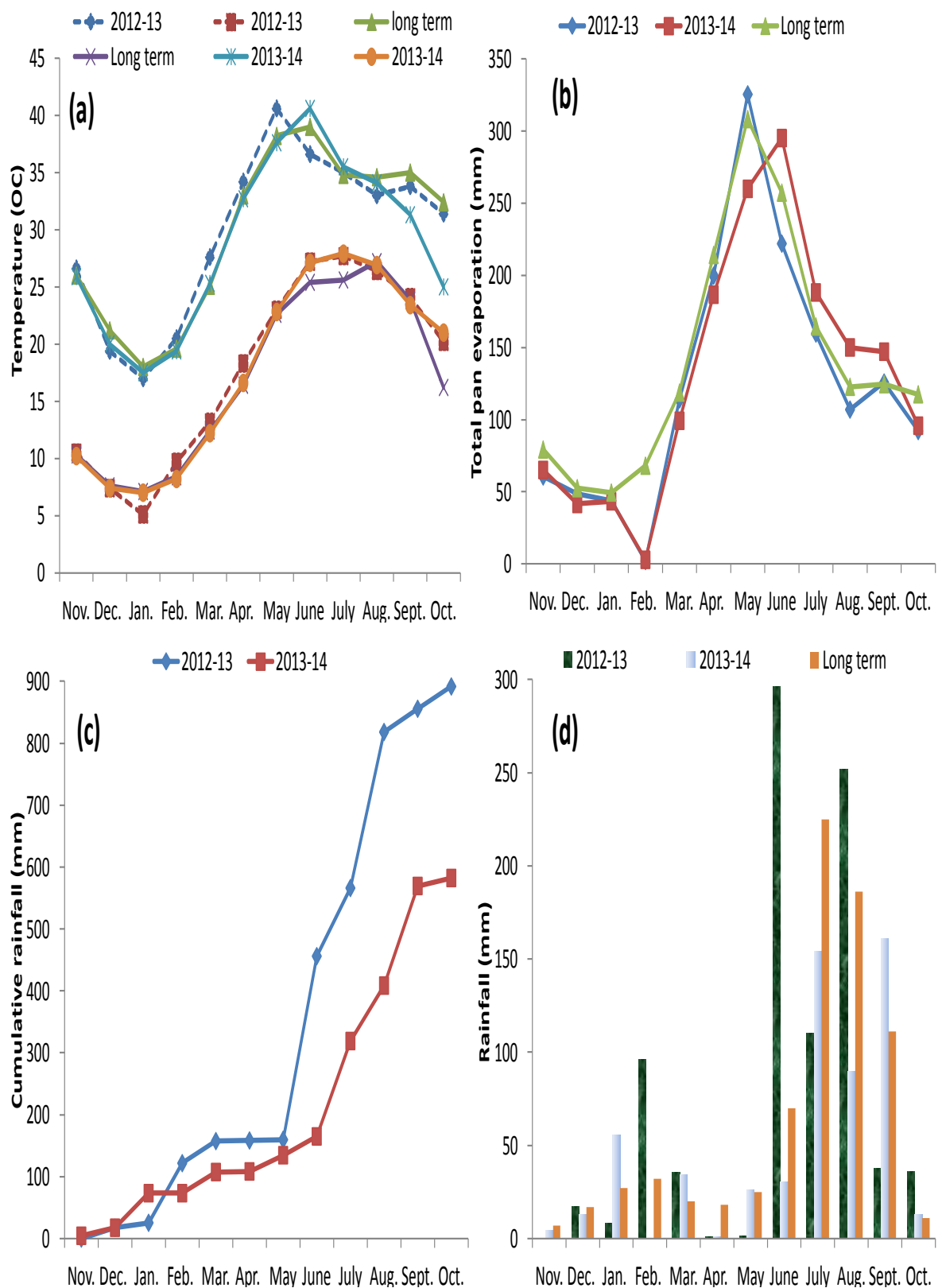


Fig. 3.1 Mean monthly maximum and minimum temperatures (a), pan evaporation (b), cumulative rainfall (c) and monthly rainfall distribution (d) during the study period (2012-14).

Table 3.3 Abbreviations and details of tillage, crop establishment and residue management under the experiment

	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice
	Abbreviations		Field preparation		Sowing/Transplanting		Residue fate	
1	CTW	DSR-P	Conventional tillage-Three passes of disc	Puddling- Four passes of power tiller in standing water.	Sowing of seeds done with pre-calibrated seed drill	DSR-P-Drum seeder with 20 cm row to row spacing	Removed	All removed
2	CTW	DSR-CT	plough followed by two passes of cultivator	Puddling done twice one a day before and one on sowing day	at a row to row 20 cm spacing at 112.5 kg ha ⁻¹ .	used to sow pre-germinated seeds on puddle plots.	-do-	-do-
3	CTW	DSR-ZT	followed by one planking.			DSR-CT-Seed drill used to sow seeds at 20 cm spacing in conventionally tilled plots.	-do-	-do-
4	CTW	MT-P		Conventional tillage-Three passes of disc plough followed by two passes of cultivator followed by one planking			-do-	-do-
5	CTW	MT-CT					-do-	-do-
6	CTW	MT-ZT					-do-	-do-
7	ZTW	DSR-P	Zero tillage-No tillage operation performed		Direct drilling of wheat seeds in standing rice stubbles under untilled conditions	DSR-ZT-Same as above in un-tilled plots.	4.4 t ha ⁻¹ retained -	-do-
8	ZTW	DSR-CT				MT-P-Mechanical transplanting using mat type nursery at 30 cm row to row spacing with 17 cm plant to plant spacing in puddled plots	-do-	-do-
9	ZTW	DSR-ZT		Zero tillage-No tillage operation performed			-do-	-do-
10	ZTW	MT-P					-do-	-do-
11	ZTW	MT-CT					-do-	-do-
12	ZTW	MT-ZT				MT-CT- Same as above except transplanting in conventionally tilled plots.	-do-	-do-
						MT-ZT-Same as above except transplanting in un-tilled plots.		

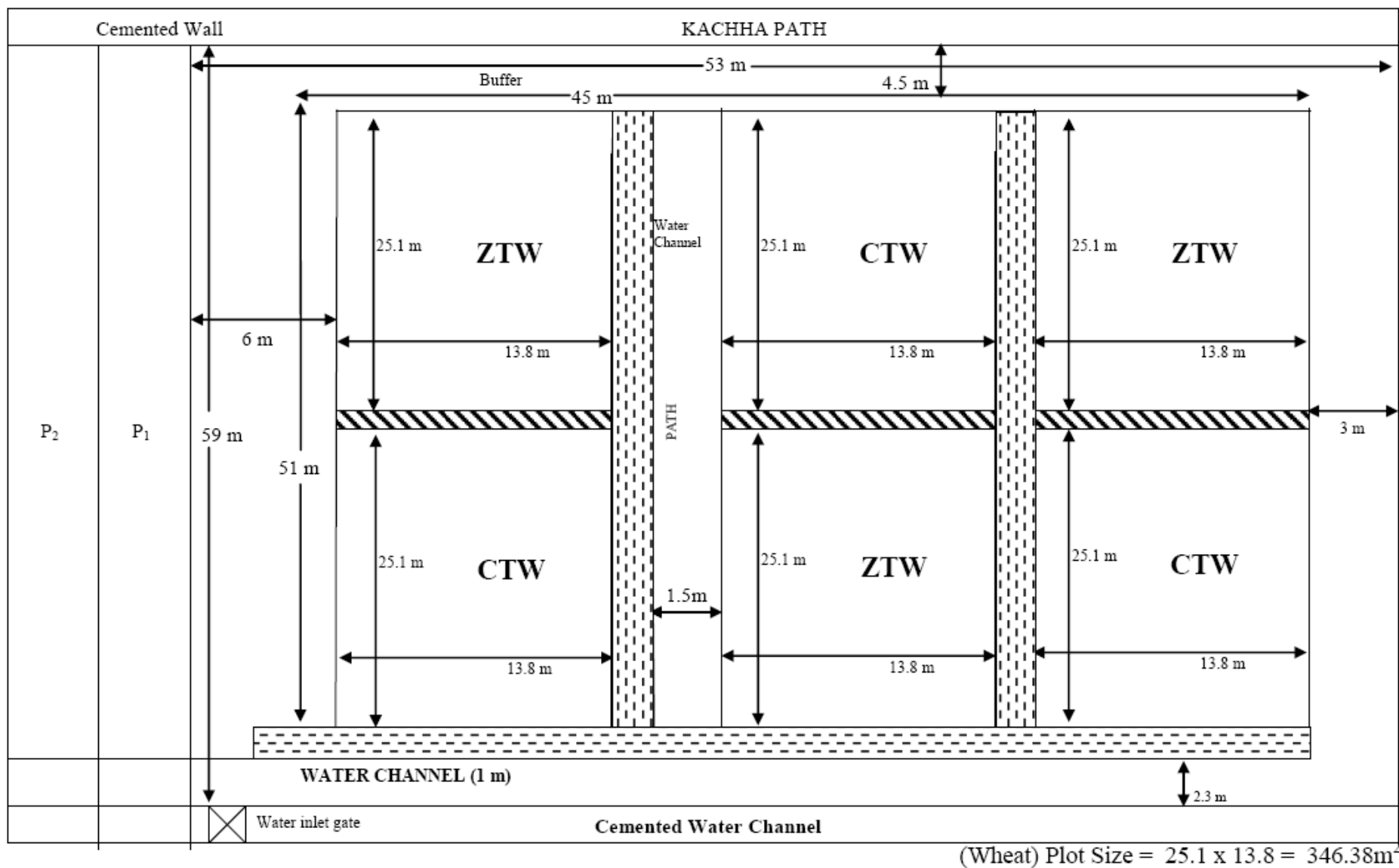


Fig. 3.2 Layout of main treatments during Rabi 2012-13

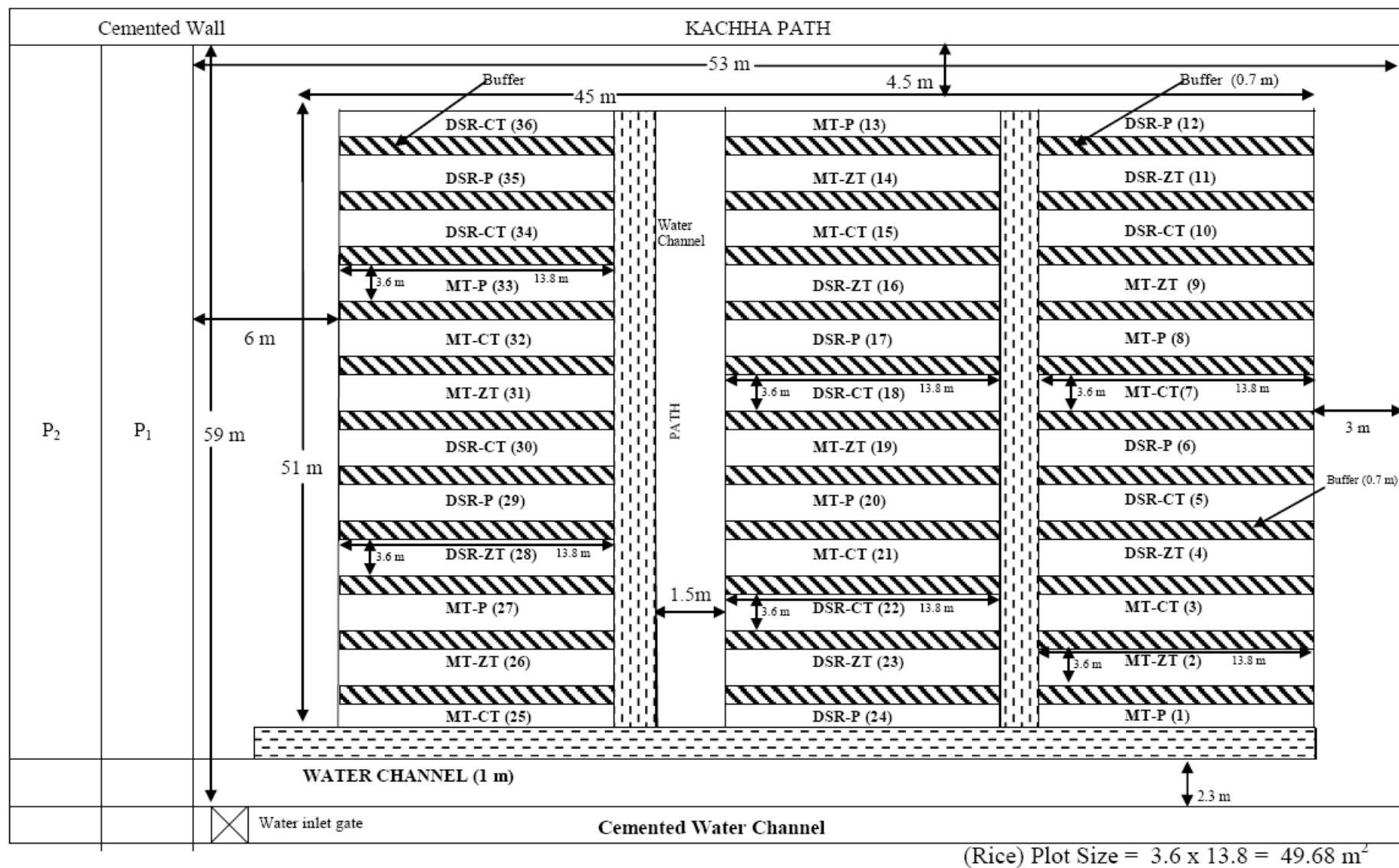


Fig. 3.3 Layout of sub and sub-sub treatments during Kharif 2013



Fig. 3.4 Different field operations carried out during the experiment viz. (a) disking, (vb) ploughing, (c) planking, (d) calibration of seed drill, (e) sowing in conventionally tilled and in (f) zero tilled plots

The treatments were replicated thrice in split-split plot design. The rice and wheat crops were irrigated on the basis of soil matric potential (15 kPa at 15-20 cm depth in rice and 35 kPa at 30-35 cm in wheat) using electronic tensiometers installed in each plot. The irrigation water amount was measured for each plot using area-velocity method/digital flow meter installed at the mouth of the plot.

Twelve combinations of different tillage and establishment methods were tested in the rice-wheat cropping sequence (Table 3.3). The treatments consisted of zero- (direct-drilling of wheat seeds in standing stubbles of the previous crop, ZTW) and conventional-tillage (disked twice followed by 2 passes of tractor-drawn cultivator and one planking, CTW). The main plot size was 13.8 m × 25.1 m (Fig. 3.2) and sub-sub plot size was 13.8 x 3.6 (Fig. 3.3). The DSR and MTR were established as per the recommendations of Punjab Agricultural University, Ludhiana.

3.4.2 Crop raising

3.4.2.1 Wheat

Pre-sowing irrigation was applied before sowing of wheat. For conventional tillage, the plots were disked twice with tractor-drawn disks to chop the stubbles followed by two passes of tractor-drawn cultivator at field capacity moisture content (Fig 3.4a-b). The soil was planked to create a fine layer of soil at the surface (Fig 3.4c). The wheat was directly drilled in standing stubbles of previous rice crop of 4.4 t ha⁻¹ with Happy Seeder at field capacity soil moisture in the first fortnight of November during both the years (Fig. 3.4f). The wheat cultivar PBW-621 was sown at a seed rate of 112 kg ha⁻¹ at row spacing of 20 cm. The seed drill was calibrated for seed rate before actual sowing of the crop (Fig. 3.4d). The dates of sowing and harvesting of wheat during both seasons shown in Table 3.4. The di-ammonium phosphate (DAP) and muriate of potash (MOP) was applied @ 138 and 50 kg ha⁻¹ at the time of sowing. The nitrogen was applied as urea in two splits @ 113 kg ha⁻¹ at sowing and 30 days after sowing (DAS). The crop was harvested in the third week of April during both the years.

3.4.2.2 Rice

The rice crop (var. PR-115) was established as puddle (P), dry-till (CT) and zero-till (ZT) under both the establishment methods viz. direct-seeded and mechanical transplanting (Fig. 3.3) as described below. The dates of sowing/transplanting and harvesting of rice seeds/seedlings during both seasons shown in Table 3.4.

3.4.2.2.1 Direct seeding of rice

The rice seeds were directly sown in conventionally tilled and zero tilled plots using zero till drill at 20 cm row to row spacing while for wet seeding the drum seeder was used to drop the sprouted seeds in the puddle soil at a row to row space of 20 cm @ seed rate of 40 kg

ha⁻¹. For sprouting, the seeds were soaked in water for 8 hours followed by water changing after every 3 hours for three times. Then, the seeds were air-dried under shade and covered by wetted jute bags to ensure that the seed just start sprouting. Every care was taken so as not to allow seeds to germinate fully as it could hinder the sowing with the help of the drum seeder through its holes which were at 20 cm spacing.

The puddling was done after a pre-puddling tillage under field capacity moisture condition. Two passes of hand-driven power tiller in ponded water were carried out to accomplish the puddling process (Fig. 3.5a). For direct seeding of rice in puddle soil, pre-germinated seeds were sown using drum seeder @ 40 kg ha⁻¹ at row spacing of 20 cm (Fig. 3.5 b&d). The direct seeding of rice in CT and ZT plots was carried out by seed drill with the same seed rate and row spacing.

3.4.2.2.2 Mechanical transplanting

To prepare mat-type nursery, the farm yard manure (FYM) was mixed with soil. Plastic frames were placed over the polythene sheet spread on the ground. The frames were filled with soil uniformly up to the brim. About 3.24 kg seed was sown in about 54 mats. Seeds were covered by a thin layer of soil and water was sprinkled by a hand sprayer for proper setting of the soil. After sowing, the mats were irrigated with a mild flow and uniform level to avoid damage to newly germinated seedlings. Seedling mats were always kept wet. Seedlings were sprayed with 81 g urea after an interval of 10 days up to 30 days when seedling mats were ready for transplanting. Water was drained from the nursery field few hours before nursery uprooting.

For mechanical transplanting the 30 d old seedlings (sown at the same date as in DSR) were transplanted using Japanese mechanical transplanter at 30x17 cm spacing (Fig 3.5 c, e&f). All the plots were applied with 10 kg ZnSO₄ at the time of field preparation. The nitrogen was applied in four splits in DSR (14, 28, 49 and 70 DAS) and three splits in MTR (5, 30 and 51 DAT). The crop was sprayed twice at weekly interval with FeSO₄ solution (1 per cent) at 30 DAS/DAT.

3.4.2.3 Irrigation management

For wheat crop, after a pre-sowing irrigation, the first irrigation was applied at 28 DAS, which was common to all the plots. Further irrigations were applied on the basis of soil matric potential of -35 kPa at 35 cm depth (S S Kukal, Personal Communication). The last irrigation to wheat crop was applied 10-15 days before the crop harvest. The details of different water inputs viz. applied irrigation water and received rainfall amounts is shown in Table 3.5.

In rice crop, the puddled plots were irrigated to ensure ponded water conditions till 15 DAT and thereafter, these were irrigated on the basis of soil matric potential of -15 kPa at 15-



Fig. 3.5 Different field operations carried out during the experiment viz. (a) puddling with power tiller, (b&d) wet seeding with drum seeder, (c) mechanical transplanting in zero tilled, (e) conventionally tilled and (f) puddled plots

20 cm depth (Kukal *et al* 2005). In conventional tilled (CT) and zero tilled (ZT) plots of DSR, the irrigations were applied every alternate day till the establishment of the crop (25-30 days) and thereafter, the plots were irrigated on the basis of soil matric potential as mentioned above. In CT and ZT plots of mechanically transplanted rice (MTR), the irrigations were applied every alternate day till 12-15 DAT for ensuring the efficacy of the applied herbicides and thereafter, the crop was irrigated as per soil matric potential mentioned above. Being transplanted late, the MTR plots received lesser rainfall (Table 3.4 and 3.5) and irrigation (Table 3.5) amounts than that of the DSR plots.

Table 3.4 Sowing, harvesting dates and rainfall amounts during 2012-2014

Field activity	Wheat 2012-13	Rice 2013		Wheat 2013-14	Rice 2014	
		DSR	MTR		DSR	MTR
Date of sowing/ transplanting	9-11-12	5-06-13	01-07-13	16-11-13	05-06-14	04-07-14
Rainfall received (mm)	158	462.3	269.8	124	323	310.5
Date of harvesting	21-04-13	10-10-13	17-10-13	23-04-14	07-10-14	15-10-14

3.4.2.4 Weed and insect-pest management

In ZT wheat plots, the weeds were managed prior to seeding by spraying glyphosate @ 1 lt ha⁻¹ while no herbicide was used in CT plots before seeding. The metsulfuron methyl (Algrip) 20 per cent WG @ 20 g ha⁻¹ and clodinafop (Topic) 15 per cent WP @ 400 g ha⁻¹ were also sprayed at 52 and 53 DAS, respectively in all the treatment plots. The crop was protected against insect-pest attack by spraying chloropyriphos @ of 2.5 l ha⁻¹ at 57 DAS in all the treatment plots. The DSR plots were sprayed with pre-emergence herbicide (pendimethline 30EC @ 2.5 l ha⁻¹) immediately after sowing. The crop was sprayed with post-emergence herbicide (bispyribac sodium 10 per cent SC @ 250 ml ha⁻¹) at 23 DAS. The weeds surviving these treatments were removed manually as and when these appeared. In puddle plots of DSR and MTR, the weeds were controlled by applying post-emergence herbicide viz. butachlor @ 150 g ha⁻¹ at 15 DAT. However, monocrotophos @ 50.4 g ha⁻¹ and propiconazole @ 62.5 g ha⁻¹ was used to control insects and diseases during the rice season. However, at harvesting the weeds were removed and weighed after sun drying for 3-4 days to record weed biomass.

3.4.2.5 Harvesting

Both rice and wheat crops were harvested as and when these matured (Fig. 3.6) and the net plots area used for harvesting was 10 m². The harvested biomass was dried and tied in bundles for respective plots.

Table 3.5 Irrigation calendar of the wheat-rice cropping system during 2012-14

Sr. No.	Conservation tillage and establishment methods	Dates of irrigations	Dates of rainfall (Figures in parenthesis are values in mm)
<i>Wheat 2012-13</i>			
1.	CTW	4/12, 24/1, 13/3	11/12 (5.5), 13/12 (8.5), 9/1 (1.5), 18/1 (9.5), 4/2 (13.5), 5/2 (2.5), 16/2 (34), 22/2 (4.5), 23/2 (31), 27/2 (5.5), 14/3 (6.5), 23/3 (23.5), 28/3 (2.0), 29/3 (1.0), 25/4 (2.0), 26/4 (6.0)
2.	ZTW	4/12, 24/1, 16/3	
<i>Rice 2013</i>			
1.	CTW-DSRP	3/6,5/6,8/6,10/6,12/6,18/6,21/6, 24/6, 26/6, 4/7, 9/7, 12/7, 16/7,22/7,23/8, 29/8, 3/9, 17/9, 2/10	6/6 (7), 13/6 (178), 15/6 (1), 17/6 (0.5), 27/6 (3), 29/6 (3), 2/7 (0.5) 4/7 (5.5), 9/7 (1), 24/7 (23), 1/8 (14.5), 4/8 (22), 6/8 (62.5), 11/8 (10.5), 16/8 (66.3), 17/8 (2), 9/9 (22.5), 25/9 (15), 28/9 (2.5), 3/10 (17.5), 9/10 (2.0), 13/10 (2.5)
2.	CTW-DSRCT	5/6,8/6,10/6,12/6,18/6,21/6, 24/6, 26/6, 4/7, 9/7, 12/7, 16/7,29/8, 3/9, 17/9	
3.	CTW-DSRZT	5/6,8/6,10/6,12/6,18/6,21/6, 24/6, 26/6, 4/7, 9/7, 12/7, 16/7,29/8, 3/9, 17/9, 24/9	
4.	CTW-MTP	29/6, 1/7, 4/7, 9/7, 12/7, 16/7, 22/7, 23/8, 3/9, 17/9, 24/9, 2/10	2/7 (0.5) 4/7 (5.5), 9/7(1), 24/7(23), 1/8 (14.5), 4/8 (22), 6/8 (62.5), 11/8 (10.5), 16/8 (66.3),
5.,	CTW-MTCT	29/6, 1/7, 4/7, 9/7, 12/7, 16/7, 22/7, 23/8, 3/9, 17/9, 24/9, 2/10	17/8 (2), 9/9 (22.5), 25/9 (15), 28/9 (2.5), 3/10 (17.5), 9/10 (2.0), 13/10 (2.5)
6.	CTW-MTZT	29/6, 1/7, 4/7, 9/7, 12/7, 16/7, 23/8, 29/8, 3/9, 17/9, 2/10	
7.	ZTW-DSRP	3/6,5/6,8/6,10/6,12/6,18/6,21/6, 24/6, 26/6, 4/7, 9/7, 12/7, 16/7,22/7,2/8, 3/9, 17/9	6/6 (7), 13/6 (178), 15/6 (1), 17/6 (0.5), 27/6 (3), 29/6 (3), 2/7 (0.5) 4/7 (5.5), 9/7 (1), 24/7 (23), 1/8 (14.5), 4/8 (22), 6/8 (62.5), 11/8 (10.5), 16/8 (66.3), 17/8 (2), 9/9 (22.5), 25/9 (15), 28/9 (2.5), 3/10 (17.5), 9/10 (2.0), 13/10 (2.5)
8.	ZTW-DSRCT	5/6,8/6,10/6,12/6,18/6,21/6, 24/6, 26/6, 4/7, 9/7, 12/7, 16/7,2/8, 3/9, 17/9	
9.	ZTW-DSRZT	5/6,8/6,10/6,12/6,18/6,21/6, 24/6, 26/6, 4/7, 9/7, 12/7, 16/7,29/8, 3/9, 17/9, 24/9	

Sr. No.	Conservation tillage and establishment methods	Dates of irrigations	Dates of rainfall (Figures in parenthesis are values in mm)
10.	ZTW-MTP	29/6, 1/7, 4/7, 9/7, 12/7, 16/7, 22/7, 23/8, 29/8, 3/9, 17/9, 24/9, 2/10	2/7 (0.5) 4/7 (5.5), 9/7 (1), 24/7 (23), 1/8 (14.5), 4/8 (22), 6/8 (62.5), 11/8 (10.5), 16/8 (66.3),
11.	ZTW-MTCT	29/6, 1/7, 4/7, 9/7, 12/7, 16/7, 22/7, 23/8, 29/8, 3/9, 17/9, 24/9	17/8 (2), 9/9 (22.5), 25/9 (15), 28/9 (2.5), 3/10 (17.5), 9/10 (2.0), 13/10 (2.5)
12.	ZTW-MTZT	29/6, 1/7, 4/7, 9/7, 12/7, 16/7, 23/8, 29/8, 3/9, 17/9, 2/10	
<i>Wheat 2013-14</i>			
1.	CTW-DSRP-CTW	10/12, 18/2, 19/3	21/12 (11), 31/12 (4.5), 18/1 (10), 21/1 (14.5), 22/1 (25), 3/2(2), 4/2 (2), 15/2 (4), 22/2 (17.5), 12/3 (2), 18/3 (12.5), 24/3 (8.5), 28/3 (3.5),6/4 (3), 17/4 (4)
2.	CTW-DSRCT-CTW	10/2, 18/2, 19/3	
3.	CTW-DSRZT-CTW	10/12,19/2,19/3	
4.	CTW-MTP-CTW	10/12, 18/2, 19/3	
5.,	CTW-MTCT-CTW	10/12, 18/2, 19/3	
6.	CTW-MTZT-CTW	10/12, 18/2, 6/3	
7.	ZTW-DSRP-ZTW	10/12, 21/2,26/3	
8.	ZTW-DSRCT-ZTW	10/12, 21/2,28/3	
9.	ZTW-DSRZT-ZTW	10/12, 6/3	
10.	ZTW-MTP-ZTW	10/12, 21/2, 20/3	
11.	ZTW-MTCT-ZTW	10/12, 18/2, 20/3	
12.	ZTW-MTZT-ZTW	10/12, 6/3	

Sr. No.	Conservation tillage and establishment methods	Dates of irrigations	Dates of rainfall (Figures in parenthesis are values in mm)
<i>Rice-2014</i>			
1.	CTW-DSRP-CTW-DSRP	7/6, 9/6, 11/6, 16/6, 18/6, 22/6, 24/6, 27/6, 30/65, 2/7, 3/7, 5/7, 9/7, 11/7, 14/7, 22/7, 14/8, 19/8, 19/9, 26/9	12/6 (10), 22/6 (12.5), 28/7 (64), 29/7 (6.0), 31/7 (9.0), 5/8 (48), 9/8 (7), 11/8 (3.5), 12/8 (7), 1/9 (34.5), 3/9 (10), 4/9 (30), 5/9 (26), 6/9 (6), 8/9 (21), 12/9 (20), 14/9 (8.5)
2.	CTW-DSRCT-CTW-DSRCT	7/6, 9/6, 11/6, 16/6, 18/6, 22/6, 24/6, 27/6, 30/6, 2/7, 3/7, 5/7, 9/7, 11/7, 14/7, 22/7, 14/8, 19/9, 26/9	
3.	CTW-DSRZT-CTW-DSRZT	7/6, 9/6, 11/6, 16/6, 18/6, 22/6, 24/6, 27/6, 30/6, 2/7, 3/7, 5/7, 9/7, 11/7, 14/7, 25/7, 19/8, 27/8, 19/9, 30/9	
4.	CTW-MTP-CTW-MTP	4/7, 7/7, 11/7, 14/7, 25/7, 14/8, 19/8, 19/9, 26/9	28/7 (64), 29/7 (6.0), 31/7 (9.0), 5/8 (48), 9/8 (7), 11/8 (3.5), 12/8 (7), 1/9 (34.5), 3/9 (10), 4/9 (30), 5/9 (26), 6/9 (6), 8/9 (21), 12/9 (20), 14/9 (8.5), 13/10 (5), 14/10 (5)
5.,	CTW-MTCT-CTW-MTCT	4/7, 7/7, 11/7, 14/7, 24/7, 12/8, 14/8, 26/8, 19/9, 26/9	
6.	CTW-MTZT-CTW-MTZT	4/7, 7/7, 11/7, 14/7, 24/7, 14/8, 26/8, 19/9, 26/9	
7.	ZTW-DSRP-ZTW-DSRP	7/6, 9/6, 11/6, 16/6, 18/6, 22/6, 24/6, 27/6, 30/65, 2/7, 3/7, 5/7, 9/7, 11/7, 14/7, 22/7, 14/8, 19/9, 26/9,	12/6 (10), 22/6 (12.5), 28/7 (64), 29/7 (6.0), 31/7 (9.0), 5/8 (48), 9/8 (7), 11/8 (3.5), 12/8 (7), 1/9 (34.5), 3/9 (10), 4/9 (30), 5/9 (26), 6/9 (6), 8/9 (21), 12/9 (20), 14/9 (8.5)
8.	ZTW-DSRCT-ZTW-DSRCT	7/6, 9/6, 11/6, 16/6, 18/6, 22/6, 24/6, 27/6, 30/65, 2/7, 3/7, 5/7, 9/7, 11/7, 14/7, 22/7, 12/8, 14/8, 25/8, 19/9, 30/9	
9.	ZTW-DSRZT-ZTW-DSRZT	7/6, 9/6, 11/6, 16/6, 18/6, 22/6, 24/6, 27/6, 30/65, 2/7, 3/7, 5/7, 9/7, 11/7, 14/7, 23/7, 14/8, 19/8, 26/8, 19/9, 30/9	
10.	ZTW-MTP-ZTW-MTP	4/7, 7/7, 11/7, 14/7, 24/7, 14/8, 26/8, 19/9, 26/9	28/7 (64), 29/7 (6.0), 31/7 (9.0), 5/8 (48), 9/8 (7), 11/8 (3.5), 12/8 (7), 1/9 (34.5), 3/9 (10), 4/9 (30), 5/9 (26), 6/9 (6), 8/9 (21), 12/9 (20), 14/9 (8.5), 13/10 (5), 14/10 (5)
11.	ZTW-MTCT-ZTW-MTCT	4/7, 7/7, 11/7, 14/7, 25/7, 14/8, 26/8, 19/9, 26/9	
12.	ZTW-MTZT-ZTW-MTZT	4/7, 7/7, 11/7, 14/7, 24/7, 14/8, 19/8, 19/9, 26/9	



Fig. 3.6 Rice crop under different establishment and tillage methods viz. (a) direct wet seeded rice, (b) CT-direct dry seeded rice, (c) ZT-direct dry seeded rice, (d) puddled mechanically transplanted, (e) CT-mechanically transplanted and (f) ZT-mechanically transplanted rice

3.4.2.6 Thrashing

The bundle weight of the harvested crop was taken from the each plot immediately before thrashing. The rice crop was thrashed manually by beating it on a drum and the wheat grains were obtained by machine thrashing. The grains were cleaned by the process of winnowing. The weight of the cleaned grains was recorded separately from the different plots in kg and converted to t ha^{-1} . Straw and seed samples were taken from the individual plots for recording grain moisture content. The grain yield of rice and wheat was finally adjusted to 14 and 12 per cent respectively.

3.5 Observations recorded

3.5.1 Soil Characterization

3.5.1.1 Soil pH

The soil pH was determined from 1:2 soil-water suspension using the method proposed by Jackson (1967).

3.5.1.2 Electrical conductivity

The electrical conductivity (EC) of the soil samples was determined in 1:2 soil water suspension equilibrated for 24 hours using conductivity bridge (Jackson 1967).

3.5.1.3 Organic carbon

Organic carbon (%) was determined using the Walkley and Black's rapid titration method as detailed by Walkley and Black (1934).

3.5.1.4 Available nitrogen

Available nitrogen was determined by modified alkaline potassium permanganate method (Subbiah and Asija 1956).

3.5.1.5 Available Phosphorus

Available phosphorus was determined by 0.5 N sodium bicarbonate extractable P by Olsen's method (Olsen *et al* 1954).

3.5.1.6 Available Potassium

Available potassium was determined by ammonium acetate extractable K (Jackson 1967).

3.5.1.7 Bulk density

Core method (Bodman 1942) was used for bulk density determination. In situ bulk density was measured after obtaining undisturbed soil cores in cylindrical rings having internal diameter of 5.3 cm and length of 5.0 cm at different soil depths. The fresh weight of soil cores was recorded and these were oven-dried at 105°C for 24 hours, and weighted to record dry weight of the cores. The bulk density was then expressed as the ratio of dry weight of soil cores (Mg) to the internal volume of the metallic rings (m^3).

3.5.1.8 Infiltration rate

The infiltration rate of field was determined using infiltrometer method (Herman 1986).

3.5.1.9 Particle size distribution

The particle size distribution of the soil samples was obtained by using international pipette method (Day 1965).

3.5.1.10 Soil moisture retention

The moisture content at the field capacity and permanent wilting point in different layers of the soil profile was determined by Pressure plate apparatus (Richard and Weaver 1943) by taking undisturbed soil cores in 7.5× 5.0 cm metallic rings.

3.5.1.11 Aggregate size distribution

The aggregate size distribution was determined by wet sieving technique (Yoder 1936). To represent aggregation status of soil, mean weight diameter (MWD) was calculated as follow

$$MWD = \frac{\sum_{i=1}^n (d_i W_i)}{\sum_{i=1}^n W_i}$$

where

d_i is the mean diameter of each size fraction in mm, n is the number of size fractions
 W_i is the weight of aggregates in the corresponding size fractions.

3.5.1.12 Hydraulic conductivity

Saturated (using guleph permeameter) and unsaturated (using disk permeameter) hydraulic conductivities were measured in-situ in the surface soil (0-10 cm).

3.5.1.13 Soil temperature monitoring

Variations in soil temperature at 0-5 cm were recorded in all the treatment plots using digital soil thermometers during wheat 2013-14, rice 2014 and during intervening periods after each wheat season.

3.5.2 Plant characteristics

3.5.2.1 Periodic biomass

The crop biomass accumulation ($t\ ha^{-1}$) was measured every fortnight in 1-m row length at two places from each plot. Sub-samples of the biomass samples were dried at 60°C for 72 h and weighed.

3.5.2.2 Periodic tiller count

Periodic tiller density (number m^{-2}) was measured in 0.5-m row length at four fixed places in each plot.

3.5.2.3 Leaf area index

Periodic leaf area index (LAI) was measured using a Delta-T Sunscan probe. Measurements were made across five rows, with the probe parallel to the rows, at one fixed location in each plot.

3.5.2.4 Effective tillers

The numbers of tillers bearing panicle were counted with the help of scale from 1-m row length, and expressed as effective tillers m⁻².

3.5.2.5 Panicle length

Ten panicles were selected at random from each plot and their length was measured and average length of panicle expressed as cm.

3.5.2.6 Number of spikelets

The ten panicles were selected randomly to count the number of spikelets panicle⁻¹ at harvest and data was presented as number of spikelets panicle⁻¹ by taking the average values.

3.5.2.7 Number of grains

The number of grains panicle⁻¹ were counted from randomly selected ten panicles at harvest and data was presented as number of grains panicle⁻¹ by calculating the average values.

3.5.2.8 Floret fertility per centage

The floret fertility per centage in rice was measured by randomly selecting 10 panicles from each plot at harvest. The filled and unfilled florets per panicle were counted and fertility per centage calculated as the ratio of filled by total florets from each panicle.

3.5.2.9 Average grain weight

For measuring average grain weight, 1000 fresh grains were counted with seed counter and expressed at 14 per cent and 12 per cent moisture content for rice and wheat crops respectively.

3.5.2.10 Grain yield

For recording the grain yield (t ha⁻¹), an area of 10 m² was harvested from the centre of each plot, thrashed manually for rice and by mechanical thrasher for wheat. The moisture content of the grains was measured using grain moisture meter and the crop yield adjusted at 12 per cent moisture for wheat and 14 per cent for rice using the following formula:

$$\text{Rice grain yield (t ha}^{-1}\text{)} = \frac{\text{Net grain yield (kg)}}{\text{Net harvested area (m}^2\text{)}} \times 10 \times \frac{(100 - M_h)}{(100 - 14)}$$

$$\text{Wheat grain yield (tha}^{-1}\text{)} = \frac{\text{Net grain yield (kg)}}{\text{Net harvested area (m}^2\text{)}} \times 10 \times \frac{(100 - M_h)}{(100 - 12)}$$

Where, M_h is the grain moisture per cent at the time of harvesting

3.5.2.11 Straw yield

Bundle weight was recorded before threshing and straw weight (kg) was recorded after deducting grain weight (kg) from the whole bundle weight (kg), which was then expressed in t ha^{-1} . The straw yield of both the crops was adjusted to zero per cent moisture content.

3.5.2.12 Harvest index

Harvest index was calculated as the ratio of grain yield to the total biological yields (grain+straw yield).

3.5.3 Soil water balance componenets

3.5.3.1 Irrigation amount

The irrigation water amount (mm) was measured using digital flow meter installed at the mouth of each plot to a depth of 5 cm in wheat and 7.5 cm in rice during each irrigation.

3.5.3.2 Rainfall

Rain fall amount (mm) was determined on the rainy day using rain gauge installed at the experimental site, itself.

3.5.3.3 Evaporation

The evaporation from the soil surface of growing crop was measured using mini-lysimeter. The minilysimeter consisted of two cylindrical PVC tubes. The outer tube was 0.20 m in diameter and 0.20 m long, whereas the inner tube was 0.15 m in diameter and 0.20 m long. The inner tube was covered by porous end cap at the bottom end, whereas the outer was open at both the ends. The cylindrical auger was used to make a hole of diameter equivalent to that of the outer PVC tube which was inserted in the hole of 0.20 m long. The undisturbed soil cores were obtained in the inner PVC tube at weekly interval during wheat season and after every irrigation/rainfall during rice season. The end caps was put on the bottom end of the inner tube and placed in the outer tube. The weight of the inner tube was recorded daily at 0.900 hours (Fig. 3.7d). Mini-lysimeters were used (Fig. 3.7a-d) in the selected treatments to work out daily mm of water evaporated below the wheat and rice canopy which was capped and placed in outer pipes of bigger diameter. The purpose of the outer cap was to provide a location within the crop where evaporation could be regularly measured. At each sampling, the lysimeters were inserted into the plots with hammer (Fig 3.7a) and then removed using the chain-pulley arrangement (Fig 3.7b). The above ground portion of any small weeds that may have been growing in the mini-lysimeters was cut at the soil surface and removed. The mini-lysimeters were carefully removed without disturbing the soil inside lysimeter, the bottom



Fig. 3.7 Installation and measurement procedure for mini lysimeters (a) filling of lysimeter, (b) lifting of filled lysimeter using chain-pulley arrangement, (c) filled lysimeter, (d) weighing of lysimeter

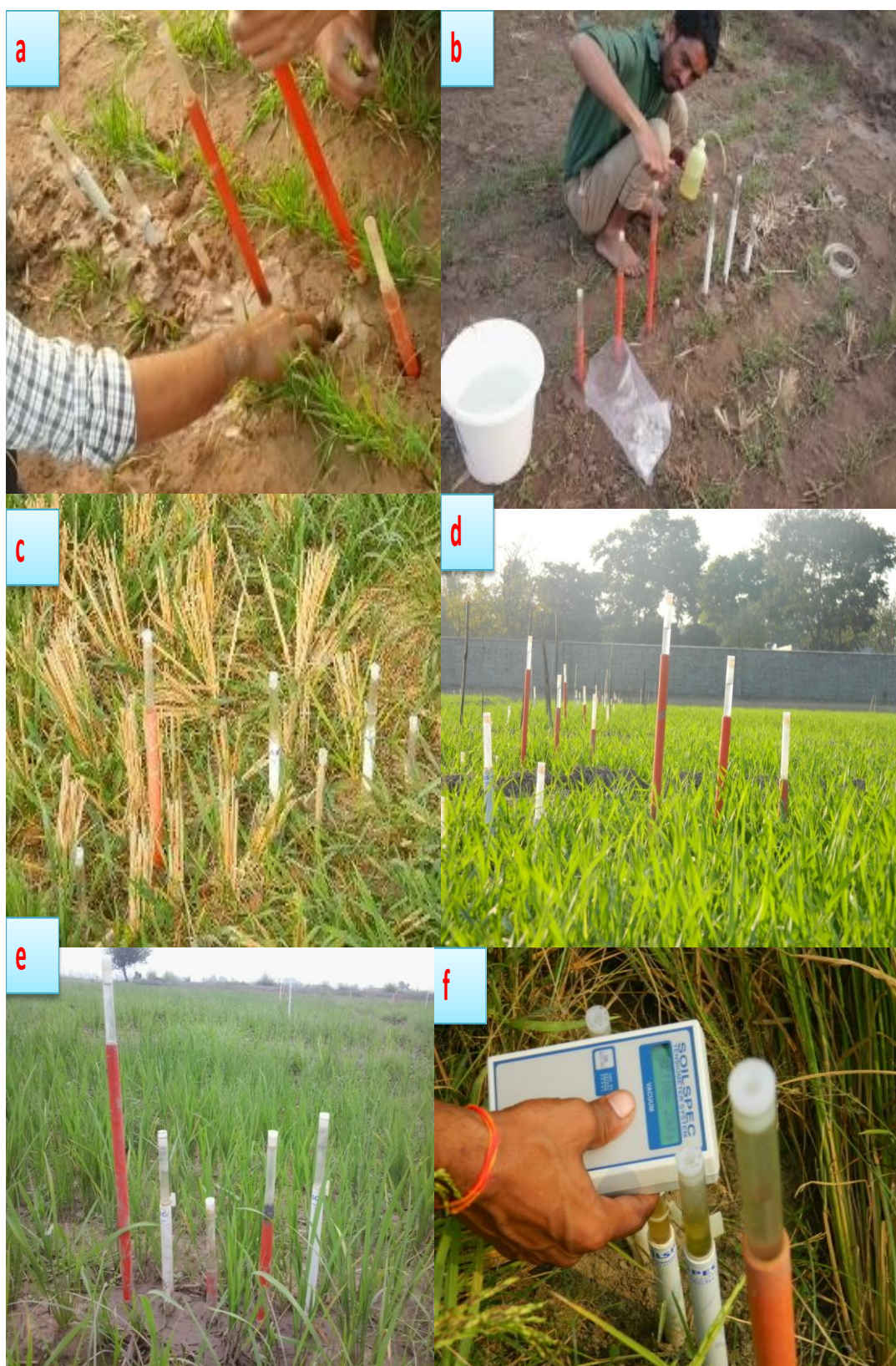


Fig. 3.8 Installation and measurement procedure of (a) tensiometers, (b) water filling and cork fixing, (c-e) tensiometers, (f) Soil-spec measuring tension readings

was levelled off, the outsides of the cylinders were cleaned and dried, and a clean cap was fitted to the bottom. Each lysimeter was weighed (Fig 3.7d) and then placed in outer cap in the experimental plot. During weighing, care was taken to ensure that no damage occurred to the soil surface.

3.5.3.4 Drainage

The daily drainage was recorded during rice (for wheat drainage assumed to be zero) by installing electronic tensiometers (Fig. 3.8f) at 45 and 60 cm in selected treatment plots (assuming rhizosphere of 50 cm). Using unsaturated hydraulic conductivity of the transitional layer, the flux was calculated on daily basis and expressed as deep drainage.

3.5.3.5 Seepage

The seepage of water during rice season was calculated from the difference in water level in the whole plots and infiltration rings embedded till the hardpan to a depth of 30 cm during flooding/irrigation.

3.5.3.6 Profile moisture content

Soil profile (at depth interval of 0-15, 15-30, 30-60, 60-90, 90-120 and 120-150 cm) moisture distribution was measured thermo-gravimetrically before sowing and after harvesting of each crop. The moisture content was then expressed in mm of water and added up for each layer to obtain profile moisture storage.

3.5.3.7 Soil matric potential

Soil matric potential was determined by the electronic tensiometers on the daily basis (Fig 3.8a-f). The tensiometers were installed at 10, 20, 30, 45, 60, 90 and 120 cm during wheat season and 10, 15, 30, 45 and 60 cm during rice season (Fig. 3.8a,b). Soil matric potential was measured using the digital SoilSpec vacuum gauge every morning at 0930 hours (Fig. 3.8f).

3.5.4 Water productivities

3.5.4.1 Irrigation water productivity

Irrigation water productivity (WP_I) was calculated as the ratio of the recorded grain yield ($Mg\ ha^{-1}$) to the total amount of applied irrigation water (mm) and expressed as $g\ kg^{-1}$.

3.5.2 Input water productivity

Input water productivity (WP_{I+R}) was calculated as the ratio of grain yield ($Mg\ ha^{-1}$) to the sum of irrigation water and the rainwater amount (mm) and expressed as $g\ kg^{-1}$.

3.5.3 Real water productivity

The real water productivity (WP_{ET}) was calculated as the ratio of grain yield ($Mg\ ha^{-1}$) to the total water used for evapo-transpiration (mm) and expressed as $g\ kg^{-1}$.

3.6 STATISTICAL ANALYSIS

The data so obtained was analyzed by Analysis of Variance (ANOVA) using GenStat V.10.3 software. The comparisons of treatment means was made by Least Significant Difference (LSD) at 5 per cent level of probability.

CHAPTER IV

RESULTS AND DISCUSSIONS

The data so obtained and analysed for the present investigation entitled “**Soil water dynamics and water productivity of rice-wheat system under different establishment methods**” are presented and discussed in the following heads

4.1 CROP PERFORMANCE AND IRRIGATION WATER PRODUCTIVITY

4.1.1 Crop performance

4.1.1.1 Wheat

4.1.1.1.1 Growth parameters

4.1.1.1.2 Yield parameters

4.1.1.1.3 Grain yield

4.1.1.2 Rice

4.1.1.2.1 Growth parameters

4.1.1.2.2 Yield parameters

4.1.1.2.3 Grain yield

4.1.2 Irrigation water productivity

4.1.2.1 Wheat

4.1.2.2. Rice

4.1.3 Cropping system productivity

4.1.3.1 Land productivity

4.1.3.2 Irrigation water productivity

4.2 SOIL WATER BALANCE AND WATER PRODUCTIVITY

4.2.1 Soil water balance components

4.2.1.1 Wheat

4.2.1.2 Rice

4.2.1.3 Wheat-rice system

4.2.2 Water productivities of wheat-rice system

4.2.2.1 Irrigation water productivity

4.2.2.2 Input water productivity

4.2.2.3 Real water productivity

4.2.3 Profile water dynamics

4.2.3.1 Wheat

4.2.3.2 Rice

4.2.3.3 Intervening period between wheat and rice

4.3 SOIL PHYSICAL ENVIRONMENT

4.3.1 Bulk density

4.3.2 Soil moisture retention

4.3.3 Infiltration

4.3.4 Aggregation

4.3.5 Hydraulic conductivity

4.3.6 Soil temperature

4.1 CROP PERFORMANCE AND IRRIGATION WATER PRODUCTIVITY

4.1.1 Crop performance

4.1.1.1 Wheat

4.1.1.1.1 Growth parameters

The crop stand and growth in all the treatment plots was generally good during both the years as indicated by the coefficient of variation of biomass production within the treatments, which ranged from 2.1 to 27.4 per cent during 2012-13 and 2.5 to 31 per cent during 2013-14. The wheat biomass in ZTW plots during 2012-13 was slightly lower than that in CTW plots till 110 DAS but later on the biomass was higher in ZTW plots than in the CTW plots (Fig. 4.1a). It was 11 per cent higher at 131 DAS and the difference decreased to 6 per cent at 156 DAS. During 2013-14, the wheat biomass was similar in ZTW and CTW plots throughout the crop season (Fig. 4.2a). The residual effect of the rice establishment method on wheat biomass was not observed at all the observed growth stages (Fig. 4.2b).

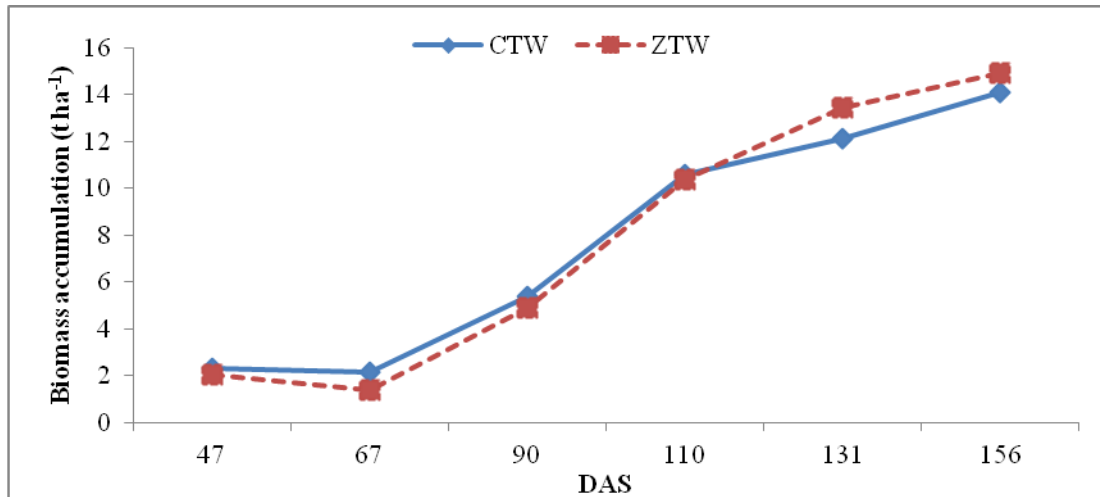
The tiller density of wheat was initially higher in CTW plots than in ZTW plots during both the years (Fig. 4.1b, 4.2d), but it was similar during the later growth stages with respect to tillage in wheat and rice and rice establishment method (Fig. 4.2e-f). The leaf area index (LAI) of wheat was higher in CTW than in ZTW plots at all the crop stages during both the years (Fig. 4.1c, 4.2g). It was statistically similar with respect to establishment method (Fig. 4.2h) and tillage in rice (Fig. 4.2i).

4.1.1.1.2 Yield parameters

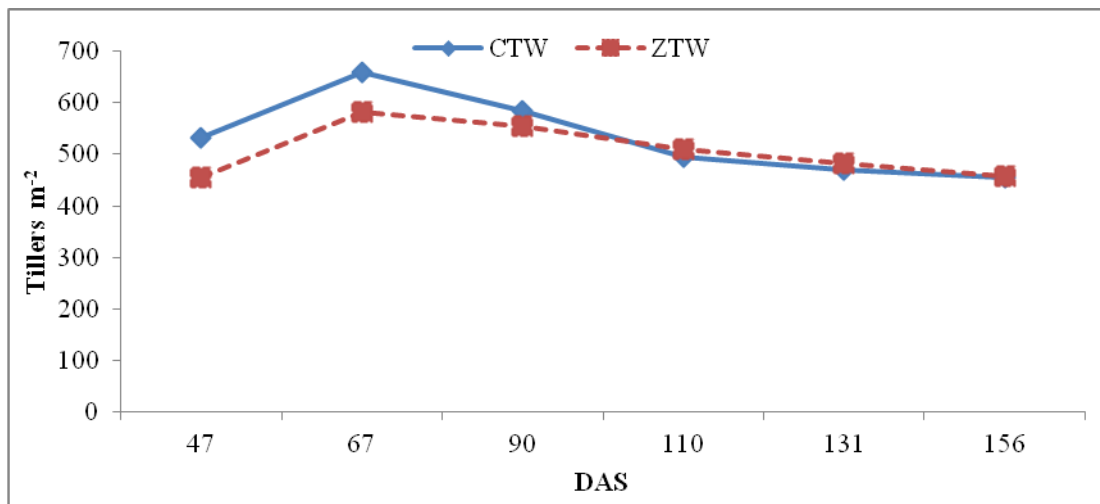
The yield attributes viz. grains per panicle, average grain weight and harvest index (HI) of wheat were not affected significantly by tillage in wheat, establishment method and tillage in rice during both the years (Table 4.1, 4.2 & 4.3).

4.1.1.1.3 Grain yield

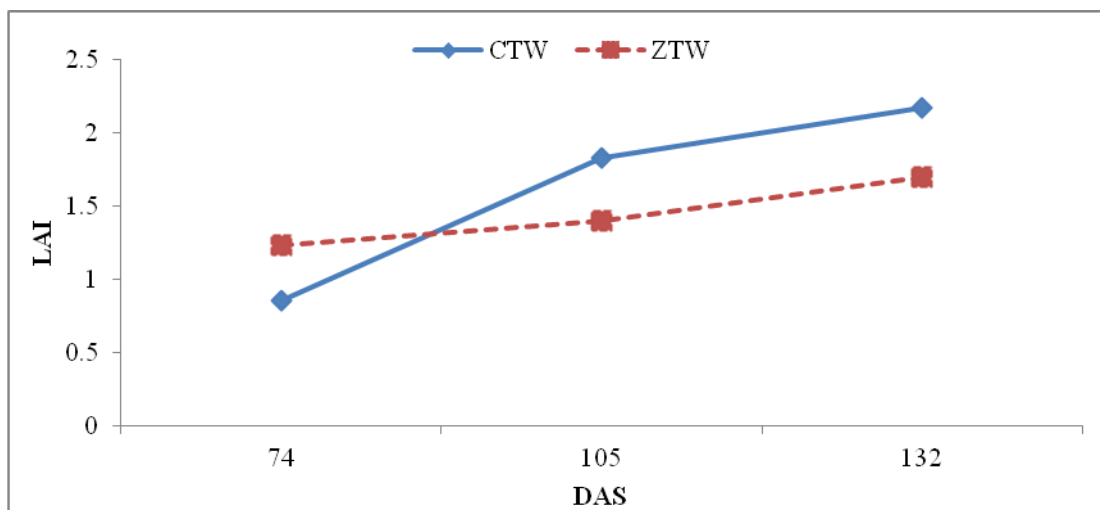
In general, the grain yield of wheat was higher in 2013-14 than in 2012-13. This could be due to the higher maximum and minimum temperatures during February-April in 2012-13 than in 2013-14. The grain yield of wheat was similar in CTW and ZTW plots during both the years. The establishment method and tillage in rice did not interact to affect the wheat grain yield significantly during 2013-14 (Table 4.4), though it was slightly higher in CTW than in ZTW plots. The difference in wheat yield decreased from 9.7 per cent in 2012-13 to 7.0 per cent in 2013-14. The wheat yield was not affected by the tillage and establishment method of rice during 2013-14 (Table 4.4).



(a)



(b)



(c)

Fig. 4.1 Effect of tillage in wheat on (a) biomass accumulation, (b) tillers density and (c) leaf area index of wheat during 2012-13

Table 4.1 Interactive effect of tillage and establishment methods on grain panicle⁻¹ and floret fertility per cent of wheat and rice during 2012-2014

Establishment methods	Tillage (Rice)	Wheat (2012-13)		Rice (2013)			Wheat (2013-14)			Rice (2014)		
		Grain panicle ⁻¹		Fertility per centage			Grain panicle ⁻¹			Fertility per centage		
		CTW	ZTW	CTW	ZTW	Mean	CTW	ZTW	Mean	CTW	ZTW	Mean
DSR	P	--	--	88.3	86.9	87.6	59.8	57.8	58.8	86.1	85.8	86.0
	CT	--	--	84.8	83.6	84.2	59.2	63.6	61.4	82.2	83.4	82.8
	ZT	--	--	81.8	79.0	80.4	52.8	60.8	56.8	77.7	75.5	76.6
Mean			--	85.0	83.2	84.1	57.3	60.7	59.0	82.0	81.6	81.8
MTR	P	--	--	80.4	80.4	80.4	61.8	59.4	60.6	68.2	74.3	71.3
	CT	--	--	79.3	77.1	78.2	58.3	53.3	55.8	70.6	68.1	69.4
	ZT	--	--	71.1	69.9	70.5	53.2	60.3	56.8	71.8	70.7	71.3
Mean		51.1	50.9	76.9	75.8	76.4	57.8	57.7	57.7	70.2	71.0	70.6
<i>Treatment means</i>												
CTW		51.1		80.9			57.5			76.1		
ZTW		50.9		79.5			59.2			76.3		
DSR				84.1			59.0			81.8		
MTR				76.4			57.7			70.6		
P				84.0			59.7			78.6		
CT				81.2			58.6			76.1		
ZT				75.5			56.8			73.9		
LSD _{0.05}												
Tillage (Wheat)		NS		NS			NS			NS		
Est Methods (Rice)				1.24			NS			2.6		
Tillage (Rice)				0.84			NS			2.8		
TW×EM(R)				NS			NS			NS		
EM(R)×T(R)				1.18			NS			3.9		
T(W) ×T(R)				NS			NS			NS		

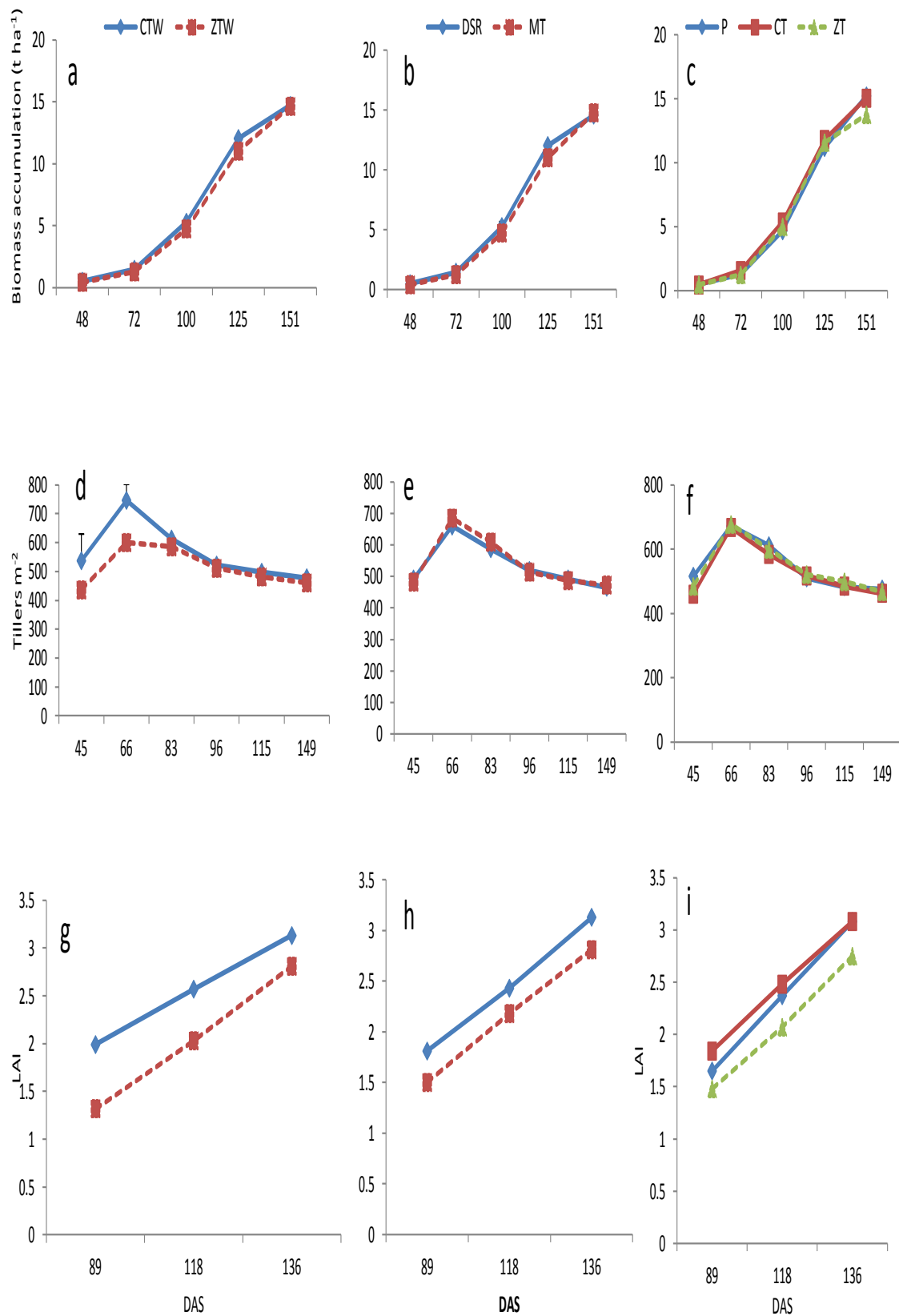


Fig. 4.2 Effect of tillage in wheat, rice establishment method and tillage in rice on (a-c) biomass accumulation, (d-f) tiller density and (g-i) leaf area index of wheat during 2013-14

Similar grain yield of wheat in CTW and ZTW plots despite of higher weed biomass (Table 4.5) in ZTW plots indicates that zero tillage can result in higher wheat productivity if the weeds are managed efficiently through effective herbicide use. In fact, zero tillage results in accumulation of weed seeds on or near to the soil surface after sowing which may encourage higher germination percentage of these seeds due to better availability of sunlight, moisture and nutrients (Singh *et al* 2015a). The zero tillage gradually increases the mechanical impediment of the surface soil, limiting the distribution of roots in plough layer (Mossaddeghi *et al* 2009). The root mass density in CT plots was 37.3 per cent higher than in the ZT plots in upper 0-15 cm soil layer during 2013-14 (data not presented).

The higher biomass during later crop growth stage (Fig. 4.2a) in 2012-13 was not reflected in wheat grain yield, though in 2013-14 it behaved similar to wheat grain yield with respect to tillage in wheat. The wheat growth, yield attributes and grain yield were not affected by tillage and establishment method of rice. The contradictory reports of wheat performance under zero tillage in the literature (Singh *et al* 2011, Guan *et al* 2015) are mainly due to the site-specific conditions related to weed intensity and soil edaphic environment affecting root proliferation and water transmission characteristics.

4.1.2.2 Rice

4.1.2.2.1 Growth parameters

The biomass of rice was non-significantly higher in CTW than in ZTW plots during 2013 (Fig. 4.3a) but there was no difference in biomass in the two treatments during 2014 (Fig. 4.4a). The establishment method of rice significantly affected the crop biomass, being higher in DSR than in the MTR plots during both the years (Fig. 4.3b, 4.4b), and the differences being higher during 2014.

The average crop biomass was significantly lower in zero-till rice than in puddle and CT plots (Fig. 4.3c, 4.4c), irrespective of the establishment method during both the years.

The tiller density was not affected significantly by tillage in wheat during both the years (Fig. 4.3d, 4.4d). It was initially higher in DSR plots but at later stages (130 DAS onwards), the MTR plots recorded higher tiller density than DSR plots during 2013 (Fig. 4e). In 2014, the tiller density though being higher initially in DSR plots was statistically similar to that in MTR plots during later stages (Fig. 4.4e). The tiller density was similar with respect to tillage in rice during both the years (Fig 4.3f, 4.4f).

The LAI was slightly higher in CTW than in ZTW plots throughout the growing season during 2013 and 2014 (Fig. 4.3g, 4.4g). It was significantly higher at 117 DAS in former than in later plots during 2013 (Fig. 4.3g).

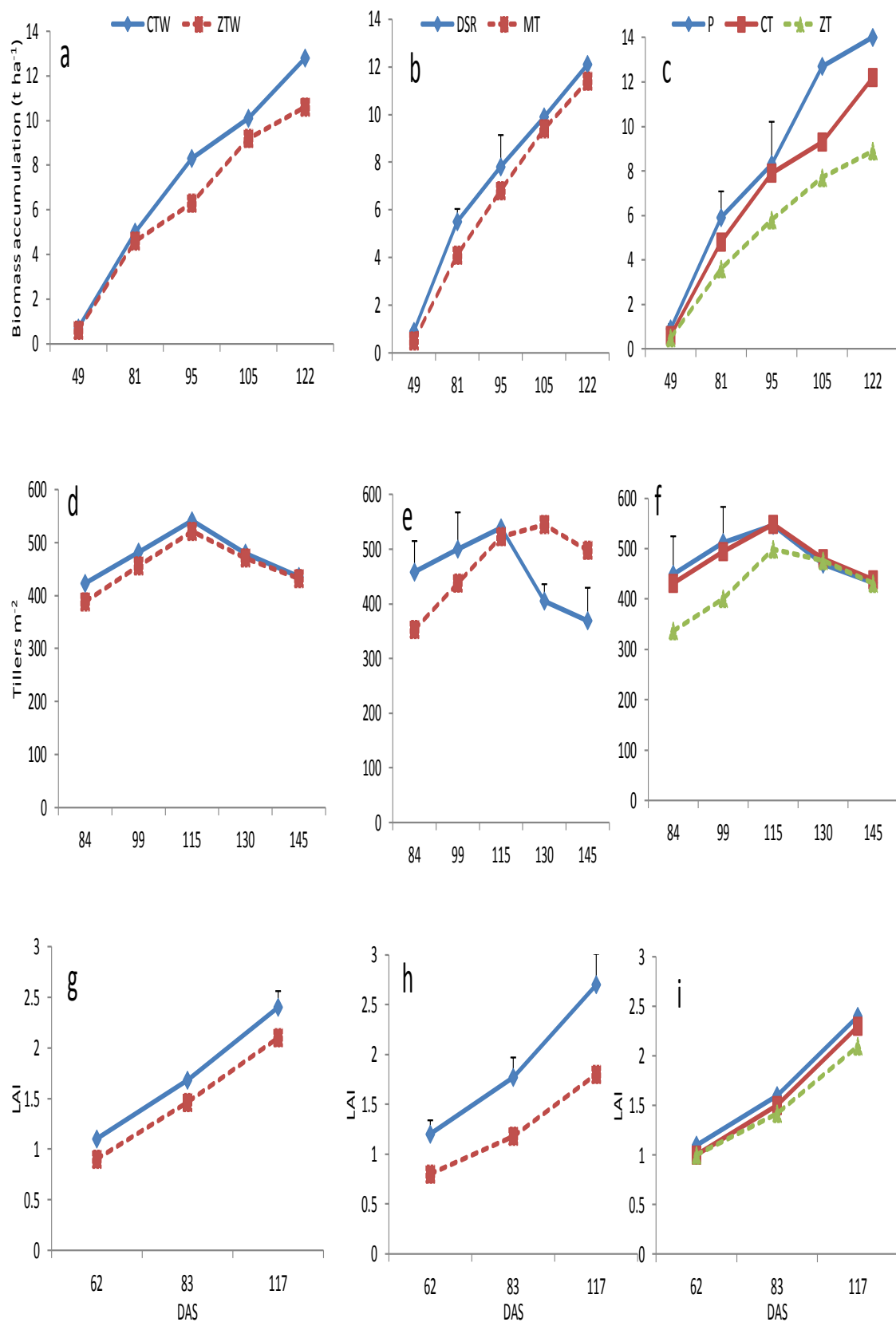


Fig. 4.3 Effect of tillage in wheat, rice establishment method and tillage in rice on biomass accumulation (a-c), tiller density (d-f) and leaf area index (g-i) of rice during 2013

The establishment method significantly affected the LAI throughout the crop growth during both the years (Fig. 4.3h, 4.4h), being higher by 50 per cent at all the crop growth stages in DSR plots than in MTR plots in 2013 and the difference increased to 115 per cent during 2014. The tillage in rice did not affect LAI in 2013 (Fig. 4.3i). However, it was significantly higher in puddle than in CT and ZT plots at 106 DAS during 2014 (Fig. 4.4i).

4.1.2.2.2 Yield parameters

The floret fertility per centage was not affected by tillage in wheat during both the years of study (Table 4.1). The DSR plots on an average had 10.1 and 15.9 per cent higher floret fertility during 2013 and 2014, respectively, than in MTR plots, the difference being significant at 5 per cent level of significance. The fertility per centage was highest in puddle followed by CT plots and lowest in ZT plots, the differences being significant in 2013. In 2014, the puddle and CT plots had similar fertility per centage, which was significantly higher than that in ZT plots.

The average grain weight was significantly higher in CTW than in ZTW plots during 2014, while in 2013 it was similar in the two treatments (Table 4.2). The DSR and MTR plots had similar average grain weight during both the years. The tillage in rice significantly affected the average grain weight of rice, being highest in puddle, followed by CT and lowest in ZT plots both under DSR and MTR. The average grain weight in 2014 was higher in puddle and CT plots of DSR as compared to MTR plots, whereas in ZT plots, the establishment method did not affect the average grain weight.

The HI was not affected by tillage in wheat during 2013 but in 2014 it was significantly higher in CTW than in ZTW plots (Table 4.3). It was highest in puddle plots, followed by CT and lowest in ZT plots under both the methods of establishment. The HI was significantly higher in ZT plots of MTR than in DSR.

4.1.2.2.3 Grain yield

The grain yield of rice was higher in CTW than in ZTW plots during both the years, the differences being statistically significant during 2014 and it was mainly because of higher weed biomass in the ZTW plots (Table 4.5). Though every effort was made to remove the weeds manually along with chemical control, still the weed growth being faster affected the main crop adversely especially in ZT plots. The grain yield of DSR was similar to that of MTR during 2013 but the difference became statistically significant during 2014, being higher in DSR. The tillage in rice significantly affected the grain yield in the order puddle > dry tilled > zero till plots during both the years. The average grain yield decreased by 17.2 per cent in 2013 and 27.7 per cent in 2014 in CT plots from that in puddle plots. It further decreased by 24.4 and 28.4 per cent in ZT plots, respectively (Table 4.4). The grain yield in 2014 was significantly higher in puddle and ZT plots of DSR than the MTR. The trend was similar in 2013 but the differences were statistically non-significant (Table 4.4).

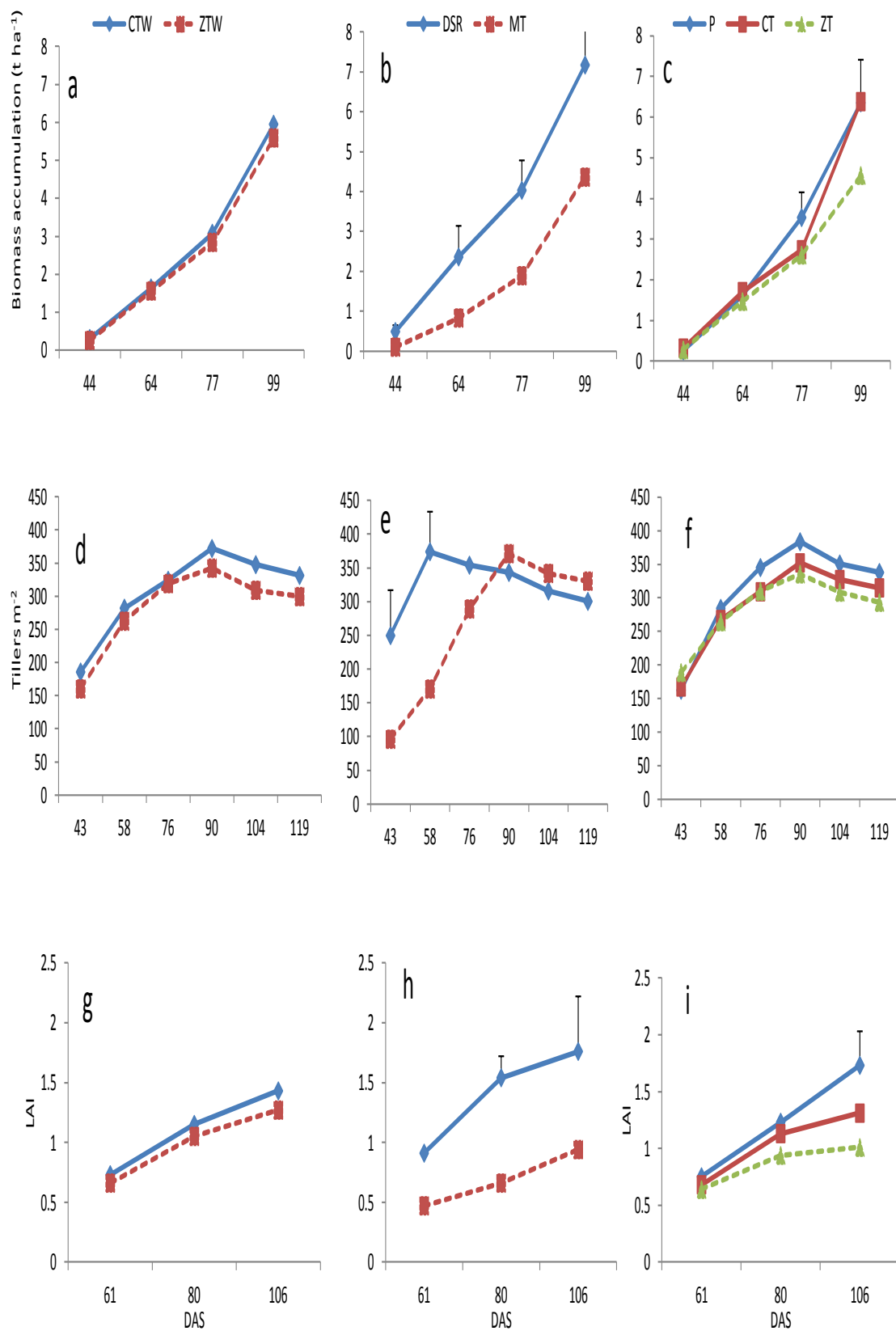


Fig. 4.4 Effect of tillage in wheat (a-c), rice establishment method (d-f) and tillage in rice (g-i) on biomass accumulation, tillers density and leaf area index of rice during 2014

Table 4.2 Interactive effect of tillage and establishment method in wheat and rice on average grain weight (mg) of wheat and rice during 2012-2014

Establishment methods	Tillage (Rice)	Wheat (2012-13)		Rice (2013)			Wheat (2013-14)			Rice (2014)		
		CTW	ZTW	CTW	ZTW	Mean	CTW	ZTW	Mean	CTW	ZTW	Mean
DSR	P	--	--	20.2	20.2	20.2	37.2	36.9	37.1	23.6	21.3	22.5
	CT	--	--	18.4	19.3	18.9	37.7	35.6	36.7	20.1	19.4	19.8
	ZT	--	--	17.9	17.2	17.6	38.0	35.2	36.6	19.6	17.8	18.7
Mean		--	--	18.8	18.9	18.9	37.6	35.9	36.8	21.1	19.5	20.3
MTR	P	--	--	22.7	19.0	20.9	38.7	34.1	36.4	23.4	21.7	22.6
	CT	--	--	18.5	17.5	18.0	35.9	37.0	36.4	20.4	19.3	19.9
	ZT	--	--	17.1	15.7	16.4	37.2	33.4	35.3	18.5	18.8	18.7
Mean		34.6	34.2	19.4	17.4	18.4	37.3	34.8	36.1	20.8	19.9	20.3
<i>Treatment means</i>												
	CTW		34.6		19.1			37.5			21.0	
	ZTW		34.2		18.1			35.4			19.7	
	DSR				18.8			36.8			20.4	
	MTR				18.4			36.1			20.3	
	P				20.5			36.7			22.5	
	CT				18.4			36.6			20.0	
	ZT				17.0			36.0			18.7	
LSD _{0.05}												
	Tillage (Wheat)		NS		NS			NS			1.11	
	Est Methods (Rice)				NS			NS			NS	
	Tillage (Rice)				1.57			NS			0.41	
	TW×EM(R)				NS			NS			NS	
	EM(R)×T(R)				NS			NS			NS	
	T(W) ×T(R)				NS			NS			0.58	

Table 4.3 Interactive effect of tillage and establishment method on harvest index of wheat and rice during 2012-2014

Establishment methods	Tillage (Rice)	Wheat (2012-13)		Rice (2013)			Wheat (2013-14)			Rice (2014)		
		CTW	ZTW	CTW	ZTW	Mean	CTW	ZTW	Mean	CTW	ZTW	Mean
DSR	P	--	--	0.26	0.23	0.25	0.43	0.41	0.42	0.28	0.25	0.27
	CT	--	--	0.23	0.23	0.23	0.40	0.42	0.41	0.24	0.25	0.25
	ZT	--	--	0.19	0.19	0.19	0.38	0.40	0.39	0.24	0.20	0.22
Mean		--	--	0.23	0.22	0.22	0.40	0.42	0.41	0.25	0.23	0.24
MTR	P	--	--	0.21	0.16	0.19	0.40	0.40	0.40	0.30	0.28	0.29
	CT	--	--	0.18	0.15	0.17	0.38	0.40	0.39	0.28	0.24	0.26
	ZT	--	--	0.17	0.16	0.17	0.39	0.41	0.40	0.20	0.18	0.19
Mean		0.447	0.448	0.19	0.16	0.18	0.39	0.40	0.40	0.26	0.23	0.25
<i>Treatment means</i>												
CTW		0.447		0.21			0.40			0.26		
ZTW		0.448		0.19			0.41			0.23		
DSR				0.23			0.41			0.24		
MTR				0.18			0.40			0.25		
P				0.22			0.41			0.28		
CT				0.20			0.40			0.25		
ZT				0.18			0.40			0.21		
LSD _{0.05}												
Tillage (Wheat)		NS		NS			NS			0.02		
Est Methods (Rice)				NS			NS			NS		
Tillage (Rice)				0.02			NS			0.02		
TW×EM(R)				NS			NS			NS		
EM(R)×T(R)				NS			NS			0.03		
T(W) ×T(R)				NS			NS			NS		

The zero tillage in wheat affected the rice grain yield, which decreased significantly during second year of study. It could be mainly due to significantly higher weed biomass in ZTW plots during both the years. Interestingly, the weed biomass in ZTW plots increased by 16.7 per cent in 2014 from that in 2013. The DSR performed better than MTR with significant difference in 2014.

The grain yield of DSR was better than MTR under all the tillage treatments in rice viz. puddle, CT and ZT. It could be due to the transplanting shock to MTR (Kamboj *et al* 2013) in comparison to DSR. Tripathi *et al* (2004) and Kamboj *et al* (2013) reported that compared with PTR, the non-puddled MTR produced 3-11 per cent higher grain yield in farmers fields. However, in the present study, the wider row spacing of MTR seedlings though resulted in higher tiller density (Fig. 4.3e, 4.4e), but lower fertility per centage, average grain weight and HI lowered the MTR yields. The significantly higher rice grain yield in puddle plots was mainly due to higher fertility per centage, HI and average grain weight as compared to CT and ZT plots. These effects were further compounded by higher weed biomass in ZT plots as also observed by Singh *et al* (2015a) and Singh *et al* (2015b). The severe iron deficiency in ZT plots despite of FeSO_4 sprays might have lowered the rice grain yields in ZT plots as also observed by Yadvinder-Singh *et al* (2009) and Jat *et al* (2009).

Most of the studies related to MTR (Gangwar and Singh 2010, Singh *et al* 2006, Sharma *et al* 2007) compare this technique with manual transplanting of rice instead of DSR or MTR in CT and ZT conditions.

4.1.3 Irrigation water productivity

4.1.3.1 Wheat

The irrigation water productivity (WP_1) of wheat was significantly lower in ZTW (1.81 g kg^{-1}) than in the CTW plots (2.16 g kg^{-1}) during 2012-13 (Table 4.6). However, it was similar in the two treatments during 2013-14 (Table 4.6). The establishment method and tillage in rice had no significant effect on WP_1 during 2013-14. The average WP_1 of wheat was similar in puddled and CT plots of rice but was significantly higher in ZT plots of rice. The decrease in WP_1 of wheat in ZTW plots from that in CTW plots was more pronounced in puddle and CT than in ZT plots of rice.

The significantly higher (2.16 g kg^{-1}) WP_1 of wheat during 2012-13 in CTW plots than in the ZTW plots (1.81 g kg^{-1}) despite of the similar irrigation water consumption is mainly due to higher grain yield of wheat in the former plots (Table 4.4) However, in 2013-14, WP_1 was statistically similar in the two tillage methods due to saving of one irrigation in the ZTW plots. In fact, the poor crop growth including the root biomass (data not presented) in ZT plots led to lower uptake of water from the root zone for transpiration compared to that in CTW plots.

Table 4.4 Interactive effect of tillage and establishment method on grain yield (Mg ha⁻¹) of wheat and rice during 2012-2014

Establishment methods	Tillage (Rice)	Wheat (2012-13)		Rice (2013)			Wheat (2013-14)			Rice (2014)		
		CTW	ZTW	CTW	ZTW	Mean	CTW	ZTW	Mean	CTW	ZTW	Mean
DSR	P	--	--	6.20	4.50	5.35	6.60	5.33	5.97	5.97	5.20	5.59
	CT	--	--	4.60	4.20	4.40	6.10	5.73	5.92	4.10	3.70	3.90
	ZT	--	--	2.90	2.90	2.90	5.23	5.40	5.32	3.70	2.97	3.34
Mean		--	--	4.56	3.86	4.21	5.97	5.49	5.73	4.59	3.96	4.28
MTR	P	--	--	5.03	4.13	4.55	5.50	5.07	5.29	5.47	4.61	5.04
	CT	--	--	4.27	3.33	3.80	5.30	5.10	5.14	3.99	3.57	3.79
	ZT	--	--	3.80	2.53	3.15	5.63	5.27	5.45	2.45	1.87	2.17
Mean		5.27	4.76	4.36	3.30	3.83	5.47	5.15	5.29	3.98	3.35	3.67
<i>Treatment means</i>												
	CTW		5.27		4.46			5.72			4.29	
	ZTW		4.76		3.63			5.32			3.65	
	DSR				4.26			5.73			4.28	
	MTR				3.83			5.29			3.67	
	P				4.95			5.63			5.31	
	CT				4.10			5.53			3.84	
	ZT				3.10			5.38			2.75	
LSD _{0.05}												
	T (W)		NS		NS			NS			0.15	
	EM(R)				NS			NS			0.14	
	T(R)				0.46			NS			0.20	
	TW×EM (R)				NS			NS			NS	
	EM(R)×T (R)				NS			NS			0.20	
	T(W) ×T (R)				NS			NS			NS	

Table 4.5 Interactive effect of tillage and establishment methods on weed biomass (Mg ha⁻¹) at harvesting in wheat and rice during 2012-2014

Establishment methods	Tillage (Rice)	Wheat (2012-13)		Rice (2013)			Wheat (2013-14)			Rice (2014)		
		CTW	ZTW	CTW	ZTW	Mean	CTW	ZTW	Mean	CTW	ZTW	Mean
DSR	P	--	--	0.58	0.65	0.62	0.10	0.19	0.45	0.72	0.76	0.74
	CT	--	--	0.75	1.02	0.89	0.25	0.48	0.36	0.86	1.11	0.98
	ZT	--	--	0.81	1.20	1.00	0.05	4.04	2.04	1.11	1.46	1.29
Mean		--	--	0.71	0.96	0.84	0.13	1.77	0.95	0.89	1.11	1.00
MTR	P	--	--	0.72	0.74	0.73	0.06	0.90	0.48	0.74	0.83	0.79
	CT	--	--	0.89	0.88	0.89	0.21	1.38	0.79	0.96	1.02	0.99
	ZT	--	--	0.92	1.27	1.09	0.09	2.58	1.34	1.15	1.54	1.35
Mean		0.27	0.39	0.84	0.96	0.90	0.12	1.62	0.87	0.95	1.13	1.04
<i>Treatment means</i>												
CTW		0.27		0.78			0.13			0.92		
ZTW		0.39		0.96			1.70			1.12		
DSR				0.84			0.95			1.00		
MTR				0.90			0.87			1.04		
P				0.68			0.47			0.76		
CT				0.89			0.58			0.99		
ZT				1.05			1.69			1.32		
LSD _{0.05}												
T (W)		0.11		0.13			0.69			0.13		
EM(R)				0.05			NS			NS		
T(R)				0.10			0.29			0.09		
TW×EM (R)				NS			NS			NS		
EM(R)×T (R)				NS			0.41			NS		
T(W) ×T (R)				0.14			0.41			0.14		

Since the plots were irrigated on the basis of soil matric potential, the lower soil water depletion in ZT plots might have resulted in saving of one irrigation. The WP_1 of wheat was not significantly affected by the establishment method (Table 4.6). Tillage in rice affected the WP_1 of wheat in 2013-14, being statistically higher in ZT than in CT plots. It was similar in puddle and CT plots. This could again be due to the similar reason as explained above.

4.1.3.2 Rice

The average WP_1 was higher in CTW than in ZTW plots during both the years, the differences being significant during 2014 (Table 4.6). The WP_1 of MTR was 31.1 per cent higher in CTW than in ZTW plots compared to 9.5 per cent during 2013 (Table 4.6). The mean WP_1 was 15 per cent higher in CTW than in ZTW plots during 2014. The average WP_1 of MTR was significantly higher than that of DSR during both the years. The WP_1 of rice in puddle, CT and ZT plots was similar in 2013 but the differences became significant during 2014. It was sufficiently higher in puddle (0.56 g kg^{-1}) than in CT (0.29 g kg^{-1}) and ZT (0.25 g kg^{-1}) plots. The WP_1 was higher by 48.9 per cent in puddle plots, 32 per cent in CT and 38.1 per cent in ZT plots of MTR than in DSR in 2014 (Table 4.6).

The higher irrigation water productivity of rice in CTW than in ZTW plots during 2014 was mainly because of higher grain yields with similar irrigation water consumption in the two treatments (Table 4.6). The significantly higher WP_1 of MTR compared to the DSR during both the years was mainly due to 23.5-63.5 per cent higher irrigation water consumed in the DSR plots. In fact, the DSR with longer crop duration in the field experienced higher evapo-transpiration losses leading to frequent irrigation as compared to MTR plots, thereby consuming higher irrigation water. The highest WP_1 in puddle plots was due to the lowest amount of the irrigation water consumption in these plots during both the years, followed by that in ZT and highest in CT plots. The lowest irrigation water consumption in puddle plots is due to three times higher infiltration rate of un-puddled as compared to puddle soil (Kukul *et al* 2009, Singh *et al* 2011, Kukul *et al* 2014). This increases the amount of irrigation water per irrigation in un-puddled plots. Moreover, the higher irrigation water consumption in CT compared to ZT plots was mainly due to the lower residence time of moving water in ZT plots particularly in the absence of any straw retention at the soil surface.

4.1.4 Cropping system productivity

4.1.4.1 Land productivity

The land productivity of wheat-rice cropping system was significantly affected by tillage in wheat during both the years. It was 15.8 and 11.3 per cent higher in CTW than in ZTW plots during 2012-13 and 2013-14, respectively (Table 4.7). The land productivity of wheat-rice was similar in DSR and MTR plots during both the years. The tillage in rice significantly affected total land productivity in both the years, being highest in puddle followed by CT and lowest in ZT plots.

Table 4.6 Interactive effect of tillage and establishment methods on irrigation water productivity (g kg^{-1}) of wheat and rice during 2012-2014

Est. methods	Tillage (Rice)	Wheat (2012-13)		Rice (2013)			Wheat (2013-14)			Rice (2014)		
		CTW	ZTW	CTW	ZTW	Mean	CTW	ZTW	Mean	CTW	ZTW	Mean
DSR	P	--	--	0.65	0.55	0.60	2.70	2.20	2.45	0.47	0.42	0.45
	CT	--	--	0.43	0.42	0.43	2.53	2.27	2.40	0.27	0.22	0.25
	ZT	--	--	0.31	0.29	0.30	2.03	3.00	2.52	0.23	0.19	0.21
Mean		--	--	0.46	0.42	0.45	2.42	2.49	2.46	0.32	0.28	0.30
MTR	P	--	--	0.81	0.66	0.74	2.30	2.07	2.19	0.70	0.63	0.67
	CT	--	--	0.47	0.36	0.42	2.10	2.10	2.10	0.34	0.31	0.33
	ZT	--	--	0.48	0.32	0.40	2.30	2.83	2.57	0.34	0.23	0.29
Mean		2.16	1.81	0.59	0.45	0.52	2.23	2.33	2.29	0.46	0.39	0.43
<i>Treatment means</i>												
CTW		2.16		0.53			2.33			0.39		
ZTW		1.81		0.44			2.41			0.34		
DSR				0.45			2.46			0.30		
MTR				0.52			2.29			0.43		
P				0.67			2.32			0.56		
CT				0.43			2.25			0.29		
ZT				0.36			2.54			0.25		
LSD _{0.05}												
Tillage (Wheat)		0.25		NS			NS			0.02		
Est Methods (Rice)				0.06			NS			0.01		
Tillage (Rice)				NS			0.22			0.02		
TW×EM(R)				0.06			NS			NS		
EM(R)×T(R)				NS			NS			0.03		
T(W) ×T(R)				NS			0.32			NS		

The significant reduction in cropping system productivity due to zero tillage in wheat was due to the yield loss both in wheat and rice (Table 4.7). Jat *et al* (2014) observed that zero tillage without mulch yielded poorly as compared to dry till plots.

The total land productivity was similar in DSR and MTR plots. The land productivity was highest (11.5 Mg ha^{-1}) in CTW-DSR-P scenario during 2012-13 and 12.6 Mg ha^{-1} during 2013-14, followed by CTW-MTR-P, CTW-DST-CT and was lowest in ZTW-MTR-ZT. The establishment method of rice does not seem to affect the productivity of wheat-rice system. Tillage in wheat on the other hand significantly affected the productivity of the cropping system. The tillage in rice played a major role in affecting the productivity of the system increasing it in the order puddle > CT > ZT (Table 4.7). Puddling might have affected the system productivity through its beneficial effects viz. destroying weed seed, reducing leaching losses (Kumar and Ladha 2011) and improving soil water retention (Kukul *et al* 2003b, Kukul and Sidhu 2004).

4.1.4.2 Irrigation water productivity

The WP_i of wheat-rice cropping system was significantly higher (16-19.5 per cent) in CTW than in ZTW plots during 2012-14 (Table 4.7). The establishment method of rice significantly affected the WP_i of the cropping system, being higher in MTR ($0.81\text{-}0.88 \text{ g kg}^{-1}$) than in DSR ($0.60\text{-}0.77 \text{ g kg}^{-1}$) plots. The tillage in rice significantly affected WP_i of the cropping system during both the years. The WP_i of wheat-rice cropping system, though similar in CT (0.76 g kg^{-1}) and ZT (0.71 g kg^{-1}) plots of rice during 2012-13, was 11.2 per cent lower in ZT plots during 2013-14. The decrease in system WP_i in 2012-13 due to zero tillage in wheat was highest (18.4 per cent) in puddle plots, followed by 15.7 per cent in CT and lowest (9.8 per cent) in ZT plots of rice. Similar trend was observed in 2013-14.

In general, the WP_i of rice was higher during 2013 than in 2014. It could be due to higher (39 per cent) and well distributed rainfall (23 rainy days) during 2013. The higher decrease in irrigation water productivity from puddle to CT plots in MTR (50.7 per cent) compared to DSR (44.4 per cent) plots may be due to significantly lower grain yield of former than in later (Table 4.7).

The zero tillage in wheat significantly decreased the average WP_i of the cropping system during both the years which was due to the lower grain yield of both the crops in zero till plots (Table 4.7). However, the higher WP_i of MTR plots compared to the DSR was due to significantly lower amount of irrigation water consumed in the former plots because of shorter duration of MTR crop in the field than that of DSR crop. The puddling resulted in highest WP_i ($0.9\text{-}1.0 \text{ g kg}^{-1}$) among all the rice tillage treatments due to higher grain yield as

Table 4.7 Interactive effect of tillage and establishment method on land (Mg ha⁻¹) and irrigation water productivity (g kg⁻¹) of rice-wheat system during 2012-14

Establishment methods	Tillage (Rice)	2012-13						2013-14					
		Land productivity (M g ha ⁻¹)			Irrigation water productivity (g kg ⁻¹)			Land productivity (Mg ha ⁻¹)			Irrigation water productivity (g kg ⁻¹)		
		CTW	ZTW	Mean	CTW	ZTW	Mean	CTW	ZTW	Mean	CTW	ZTW	Mean
DSR	P	11.5	9.26	10.4	0.96	0.86	0.91	12.6	10.5	11.6	0.83	0.71	0.77
	CT	9.87	8.96	9.42	0.79	0.72	0.76	10.2	9.43	9.82	0.58	0.50	0.54
	ZT	8.17	7.66	7.92	0.65	0.60	0.63	8.93	8.37	8.65	0.48	0.47	0.48
Mean		9.84	8.71	9.25	0.80	0.73	0.77	10.6	9.44	10.0	0.63	0.56	0.60
MTR	P	10.3	8.89	9.60	1.19	1.01	1.10	11.0	9.67	10.3	1.10	1.00	1.05
	CT	9.54	8.09	8.82	0.83	0.68	0.76	9.17	8.67	8.99	0.63	0.61	0.62
	ZT	9.07	7.29	8.18	0.87	0.68	0.78	8.10	7.14	7.62	0.84	0.72	0.78
Mean		9.64	8.10	8.87	0.96	0.79	0.88	9.41	8.49	8.98	1.29	0.78	0.82
Treatment means													
	CTW	9.74			0.88			9.99			0.74		
	ZTW	8.41			0.76			8.97			0.67		
	DSR	9.25			0.77			10.01			0.60		
	MTR	8.87			0.88			8.98			0.81		
	P	10.0			1.00			10.94			0.90		
	CT	9.12			0.76			9.41			0.58		
	ZT	8.05			0.71			8.14			0.63		
LSD _{0.05}													
	Tillage (Wheat)	0.88			0.04			0.73			0.03		
	Est Methods (Rice)	NS			0.04			NS			0.07		
	Tillage (Rice)	0.46			0.05			0.55			0.03		
	TW×EM(R)	NS			NS			NS			NS		
	EM(R)×T(R)	NS			0.07			NS			0.05		
	T(W) ×T(R)	NS			NS			NS			NS		

well as lower irrigation inputs as explained earlier. The WP_I of the cropping system was, however similar in CT and ZT plots during 2012-13 but during 2013-14, it was significantly higher in ZT plots. It is due to lower irrigation water amount consumed in both wheat and rice crops grown in ZT plots. The WP_I of both DSR and MTR was significantly higher in puddle plots than CT and ZT plots because of consumption of lower irrigation water amounts and reported higher grain yields.

4.2 SOIL WATER BALANCE AND WATER PRODUCTIVITIES

The soil water balance components and water productivities under different tillage scenarios were evaluated as discussed below

4.2.1 Soil water balance components

4.2.1.1 Wheat

The irrigation water consumption during 2013-14 was similar (331–348 mm) to that in 2012-13 (334-353 mm) was similar in ZTW and CTW plots in 2013-14 except in double zero-till plots (ZTW-DSRZT), where the irrigation water amounts was sufficiently lower (270 mm) than all other treatment combinations (341-348 mm) (Table 4.8). The lower amount of irrigation water consumed in ZTW-DSR-ZT scenario was due to the poor crop stand leading to lower uptake of water from the soil. The amount and distribution of rainfall during the two wheat seasons was almost similar.

The change in profile moisture was higher (61.6-78.2 mm) in 2012-13 than in 2013-14 (42.5-54.5 mm), thereby indicating higher use of profile water by wheat crop during first year. In 2012-13, zero tillage in wheat resulted in higher change in profile moisture ($\Delta\theta$) (or in other words, zero-till plots used more profile water than CT plots). It could be due to the higher evaporation from zero-till plots with continuity of the capillaries especially in the surface layers. However, in 2013-14, the effect of ZT in DSR was more pronounced in affecting $\Delta\theta$, being 42.5-47.1 mm in DSR-ZT plots in comparison to 54.3-54.5 mm in DSR-CT plots (Table 4.8), perhaps due to the similar reasons.

The evapo-transpiration (ET) of wheat during 2012-13 was slightly higher (430-433 mm) than that in 2013-14 (401-430 mm) (Table 4.8). It could be due to higher maximum and minimum temperatures during 2012-13 compared to 2013-14. The ET of wheat grown with zero- and conventional-tillage was similar, during 2012-13. However, during 2013-14, zero tillage in both during wheat and rice lowered the ET of wheat mainly because of poor crop biomass in double zero till plots leading to lower uptake and transpiration of water by the crop canopy.

4.2.1.2 Rice

The irrigation water used was sufficiently higher during 2014 (1526-1651 mm) than in 2013 (991-1021 mm) with 323 mm of rainfall split over 17 wet days during 2014 with 462 mm rain spread over 16 rain events during 2013 (Table 4.8). The irrigation water consumption was similar in different tillage scenarios during 2013 but in 2014, shifting from conventional tillage to mixed tillage or double zero tillage system resulted in higher irrigation water consumption. This is in contrary to the reports published in the literature on this aspect (Jat *et al* 2014). It could be due to the reason that in the present study, zero till DSR plots had no straw mulch retained on the soil surface.

The change in profile moisture storage at sowing and harvest of rice was not so conspicuous as in wheat, perhaps due to frequent irrigations in rice crop as compared to the wheat crop. The lower seepage losses during 2013 (265-462 mm) as compared to 2014 (561-732 mm) could be due to the lower irrigation water amount consumption during 2013. In double ZT system viz. ZTW-DSRZT, seepage was higher (35.7 per cent during 2013 and 16.4 per cent during 2014) as compared to the conventional system viz. CTW-DSRCT (Table 4.8). Zero tillage in wheat increased the seepage losses in DSR under both ZT and CT system, the increase being higher in DSR-CT than in DSR-ZT.

Table 4.8 Soil water balance components (mm) of wheat and rice during 2012-14

	Wheat (158 mm; 12)			Rice (462 mm; 16)				
	I+R	ET	$\Delta\theta$	I+R	ET	$\Delta\theta$	S	D
2012-13								
CTW-DSRCT	492	430.4	61.6	1457	391	2.20	284.0	780.0
CTW-DSRZT	--	--	--	1483	399	1.42	265.1	817.5
ZTW-DSRCT	--	--	--	1453	391	1.74	461.6	599.0
ZTW-DSRZT	511	432.8	78.2	1476	396	2.20	385.3	692.2
2013-14								
	Wheat (124 mm; 12)			Rice (323 mm; 17)				
	I+R	ET	$\Delta\theta$	I+R	ET	$\Delta\theta$	S	D
CTW-DSRCT	455	400.7	54.3	1849	497	2.13	561.0	788.8
CTW-DSRZT	472	429.5	42.5	1919	517	1.37	579.7	821.2
ZTW-DSRCT	466	411.5	54.5	1974	532	1.44	731.7	709.3
ZTW-DSRZT	394	346.9	47.1	1907	513	1.82	653.3	738.8

**Figures in parenthesis are the rainfall amounts and number of rainy days*

The deep drainage losses during rice season beyond 60 cm were to the extent of 36-54 per cent of the total input water used during the crop season (Table 4.8). During both the years, the deep drainage losses were lower in plots with zero tillage in wheat, but zero tillage in DSR resulted in higher deep drainage losses. Sudhir Yadav *et al* (2011b) reported that in clay loam soil, the lower irrigation input to DSR than in PTR, was due to reduced seepage and drainage losses. They further reported that 30–50 per cent reduction in irrigation water while shifting from continuous flooding to intermittent irrigation was due to significant reduction in drainage losses.

The evapo-transpiration losses in rice were higher (497-532 mm) during 2014 than in 2013 (392-399 mm). However, the ET losses of DSR were not affected by tillage both in rice and wheat. The ET constituted 27 per cent of the total input water used during both the years. The poor co-relation coefficient ($R^2=0.12$) between ET and grain yield of rice indicates that despite of the lower grain yield under zero-till conditions, the ET of the crop did not decrease. This could be due to that fact that despite of lower grain yields, the higher weed population in zero-till plots consumed water for transpiration purposes leading to similar or even higher ET under zero-till conditions.

4.2.1.3 Wheat-rice system

The total input water for wheat-rice cropping system was higher (2330-2467 mm) during 2014 compared to 1955-1993 mm during 2013. As explained earlier, higher rainfall of 173 mm during 2013 resulted in lower irrigation amounts. The tillage in wheat and rice did not affect the total input water of the cropping system during both the years (Fig. 4.5).

The deep drainage and seepage in the wheat-rice cropping system was affected by zero tillage in wheat. The deep drainage of the system during 2012-13 was 40 per cent of the total input water used in the CTW plots with DSR-CT as compared to 30.4 per cent in ZTW plots (Fig. 4.5). The corresponding values during 2013-14 were 33.8 per cent (CTW) and 28.7 per cent (ZTW), respectively. Similar was the trend in case of DSR-ZT. The tillage in rice in CTW plots did not affect the deep drainage during both the years but in ZTW plots, the zero tillage in rice increased deep drainage as compared to the conventional tillage.

Zero tillage in wheat resulted in higher seepage losses (462-732 mm) compared to conventional tillage (284-561 mm), during both the years (Fig. 4.5). The seepage losses were lower with zero tillage in rice as compared to CT in rice (DSR-CT).

The evapo-transpiration (ET) losses of the wheat-rice cropping system were higher during 2013-14 (971-1057 mm) as compared to 2012-13 (908-922 mm), which was due to the higher amount of rain (39 per cent) during 2012-13. However, the ET losses of wheat-rice cropping system including the intervening period were not affected by tillage in wheat or tillage in rice.

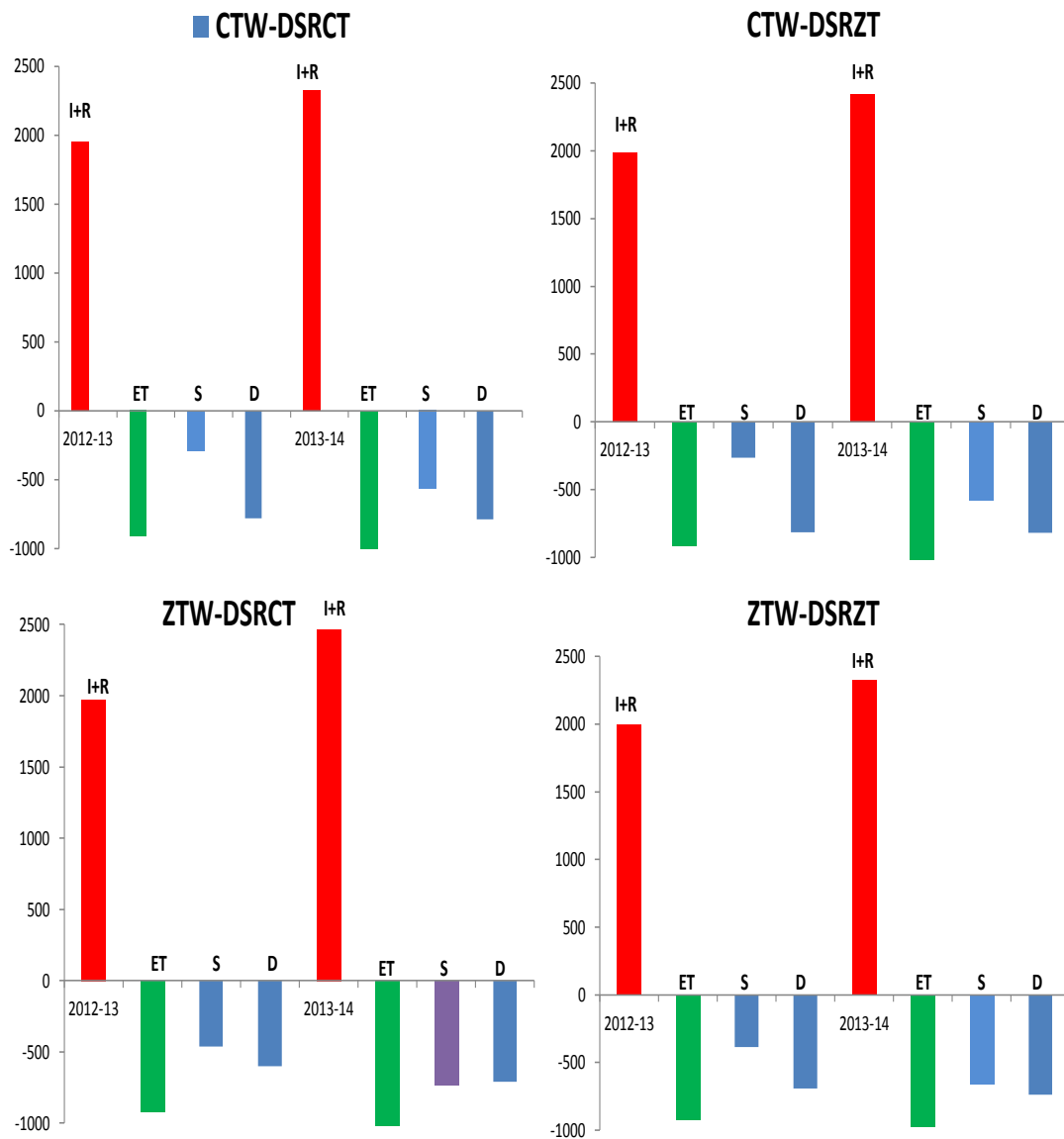


Fig 4.5 Water balance components (mm) of wheat-rice system including intervening period as affected by different tillage methods (*I+R* denotes irrigation+rain, *S* denotes seepage, *D* denoted deep drainage and *ET* denotes evapo-transpiration)

4.2.2 Water productivities of wheat-rice system

4.2.2.1 Irrigation water productivity

The irrigation water productivity (WP_I) of wheat-rice cropping system ranged from 0.56-0.74 g kg⁻¹ in 2012-13 compared to 0.45-0.54 g kg⁻¹ during 2013-14. The lower values of WP_I during 2013-14 are due to the lower amounts of rains during the year, leading to consumption of higher irrigation water amounts (Fig. 4.6). Shifting from conventional to zero-till system, resulted in decrease in WP_I being lowest in double zero- till system (0.56 g kg⁻¹ during 2012-13 and 0.45 g kg⁻¹ during 2013-14) (Fig. 4.7). The WP_I of zero-till rice in CTW plots was almost similar to that in plots with double zero till. Zero tillage in wheat

resulted in lower (18 per cent) WP_i compared to the conventional system viz. CTW-DSRCT during 2012-13. This difference decreased to 13 per cent during 2013-14.

On an average in the rice-wheat cropping system as a whole including intervening period, irrigation water amounts was higher (42 per cent) during 2013-14 as compared to 2012-13 (Fig. 4.6). Further, among different tillage scenarios, the irrigation water amount varied as: ZTW-DSRCT (48.3 per cent) > CTW-DSRZT (43.5 per cent) > CTW-DSRCT (39.7 per cent) > ZTW-DSRZT (35.6 per cent) (Fig. 4.6).

Lowest increase in irrigation water amount in the double zero till plots was mainly because of saving of one irrigation during wheat 2013-14.

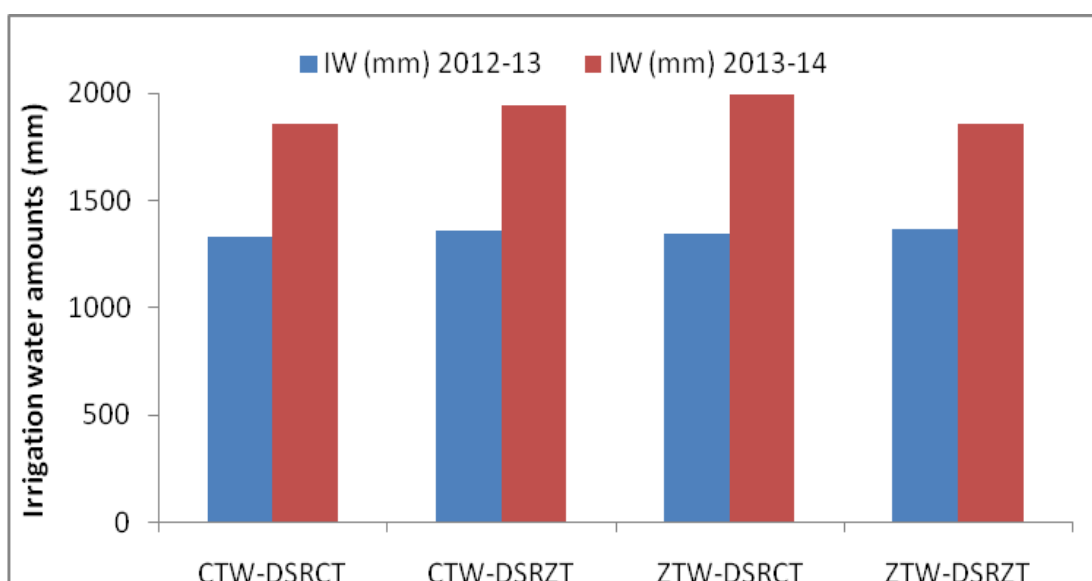


Fig. 4.6 Irrigation water amounts (mm) under different tillage methods during 2012-14

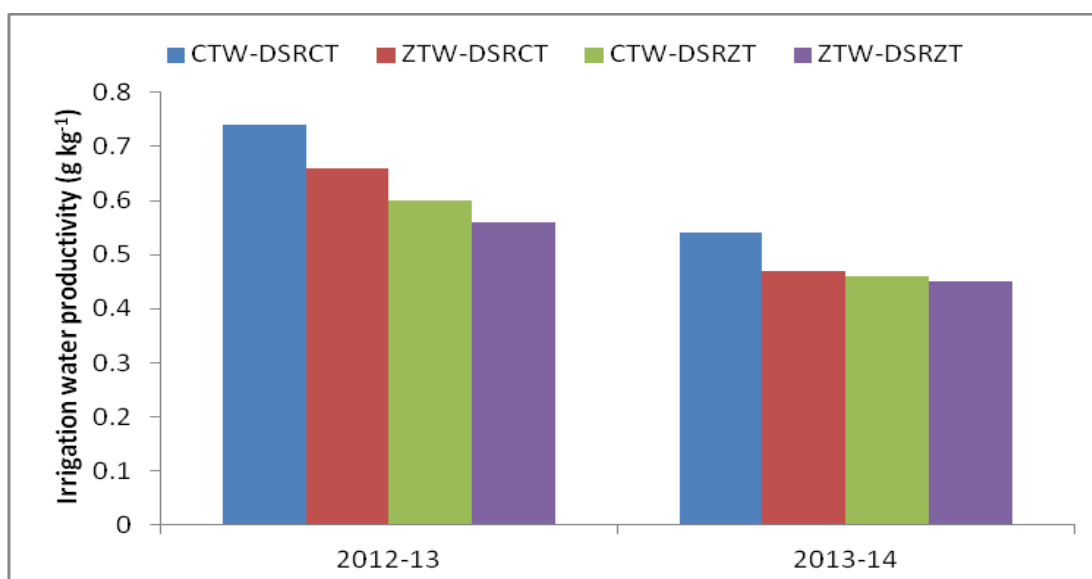


Fig. 4.7 Irrigation water productivities as affected by different tillage methods during (a) 2012-13 and (b) 2013-14

4.2.2.2 Input water productivity

The input water productivity (WP_{I+R}) of wheat-rice cropping system decreased by 34.2 per cent in 2012-13 while shifting from complete conventional tillage system to complete zero tillage system (Fig. 4.8). However, this difference decreased to 22.2 per cent in 2013-14. The total WP_{I+R} of all the system with either single or double zero tillage were almost similar during 2013-14.

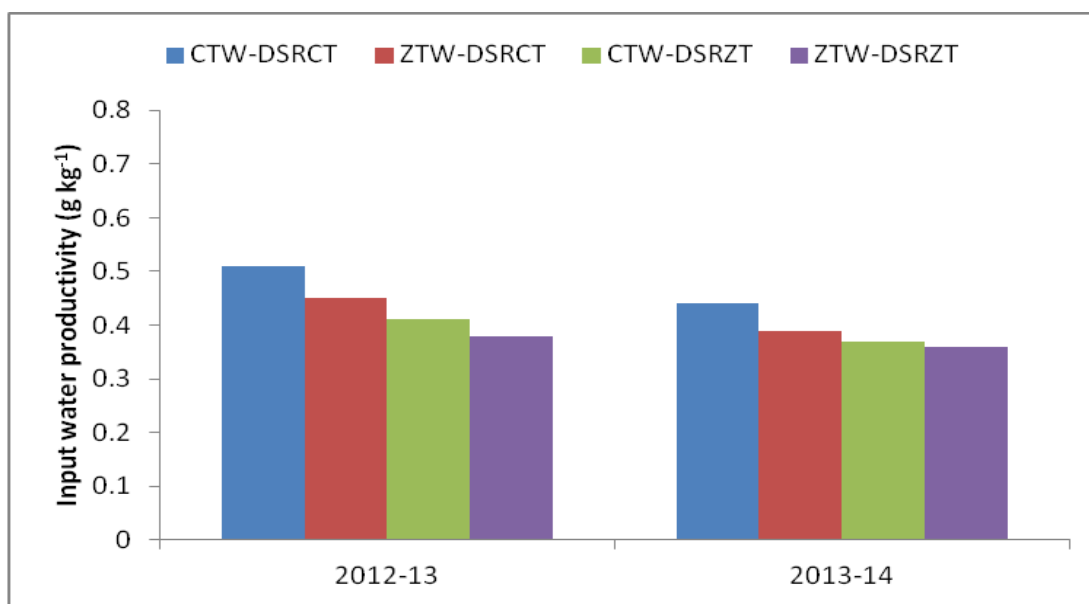


Fig. 4.8 Input water productivities as affected by different tillage methods during (a) 2012-13 and (b) 2013-14

During 2012-13, higher rainfall (39 per cent) was received as compared to that in 2013-14. The double ZT plots viz. ZTW-DSRZT recorded lowest input water productivity during both the years ($0.38\ g\ kg^{-1}$ during 2012-13 and $0.36\ g\ kg^{-1}$ during 2013-14) (Fig 4.8). Further, it was observed that CTW-DSRZT, ZTW-DSRCT and CTW-DSRCT had 7.9, 18.4 and 34.2 per cent higher values of input water productivity over the ZTW-DSRZT plots during 2012-13 and the differences decreased to 3.0, 8.3 and 22.2 per cent during 2013-14.

4.2.2.3 Real water productivity

The real water productivity based on evapo-transpiration (WP_{ET}) (Fig. 4.9) ranged from 0.83 - $1.08\ g\ kg^{-1}$ in 2012-13 to 0.86 - $1.02\ g\ kg^{-1}$ during 2013-14. The differences in real water productivity among various tillage scenarios narrowed down during 2013-14, being similar in the treatments with single or double zero tillage. The results indicate that during harsh weather conditions, the differences in WP_{ET} were not so conspicuous among various tillage conditions.

The double ZT plots (ZTW-DSRZT) had lowest WP_{ET} (0.76 g kg^{-1}) during 2012-13 while it slightly improved over CTW-DSRZT plots (0.86 g kg^{-1}) during 2013-14. The CTW-DSRZT, ZTW-DSRCT and CTW-DSRCT plots had 7.2, 18.12 and 30.0 per cent higher WP_{ET} as compared to the double ZT plots while during the second year, the ZTW-DSRZT, ZTW-DSRCT and CTW-DSRCT plots had 1.1, 3.4 and 18.6 per cent higher WP_{ET} as compared to the CTW-DSRZT plots (Fig 4.9).

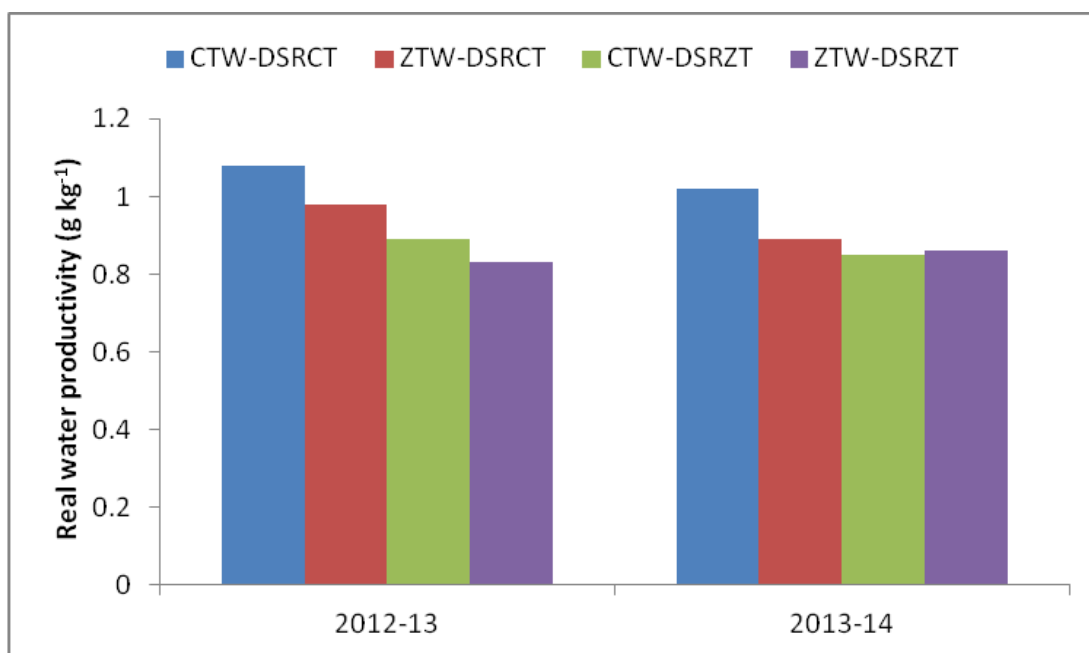


Fig. 4.9 Real water productivities as affected by different tillage methods during (a) 2012-13 and (b) 2013-14

4.2.3 Profile water dynamics

4.2.3.1 Wheat

The soil matric potential (SMP) during 2012-13 measured at 10 cm soil depth from 40 days after sowing (DAS) onwards was similar in both CTW and ZTW till 50 DAS (Fig. 4.10a). After this, the CTW plots started drying at faster rate as compared to zero-till plots till harvest. At 20 cm soil depth, the SMP till 63 DAS and thereafter indicates that the zero till plots retained higher moisture than the CTW plots (Fig. 4.10b). From 78-119 DAS, the moisture status in the two tillage systems was similar, but thereafter, CT plots dried at a faster rate. At 30 and 45 cm soil depth during 2012-13, the SMP was similar in the two treatments (Fig. 4.10c,d), whereas at 60 cm, the CTW plots behaving similarly to ZTW plots till 78 DAS, dried at a faster rate thereafter (Fig. 4.10e). Interestingly at 90 cm soil depth, the CT plots were dried faster than ZTW plots throughout the growing season (Fig. 4.10f). These fluctuations in SMP during 2012-13 at different soil depths indicate that zero tillage affected both the upward as well as downward movement of soil water into the soil.

The continuity of capillaries in zero-till plots could have resulted in upward movement of water into surface layer of plots. The presence of rice straw @ 4.4 t ha⁻¹ could be another reason for the higher wetness of the zero-till plots. Balwinder singh *et al* (2011b) in clay loam soil reported that in irrigated wheat, mulch suppressed whole season soil evaporation by 35–40 mm and resulted in higher wetness in mulched plots as compared to the unmulched plots. Similar type of observations were made with respect to SMP at different soil depth during 2013-14 except that at 90 cm the wetness of soil in all the tillage scenarios was almost similar unlike as in 2012-13 (Fig. 4.11f).

4.2.3.2 Rice

The SMP profiles at different depths (Fig. 4.12) during 2013 indicate that the zero till plots dried at a faster pace in the surface layer (10 cm) (Fig. 4.12a). The SMP did not vary much with respect to different tillage scenarios in the sub-surface layers (15-60 cm) (Fig. 4.12 b-d) due to frequent irrigations to DSR plots. However, during initial stages (43-51 DAS), double zero till plots had lowest moisture status among all the tillage scenarios except CTW-DSRCT plots in which the moisture status was similar to that in double zero till plots. Similar trend was observed in soil matric potential recorded at different depths during 2014 (Fig. 4.13).

The zero till plots are expected to dry at a faster rate due to continuity of soil pores in these plots. This is evidenced from the evaporation measured during the rice season, which was sufficiently higher (36 per cent in 2013 and 22 per cent in 2014) in complete zero till system than in conventional system of tillage in DSR plots (Fig 4.14).

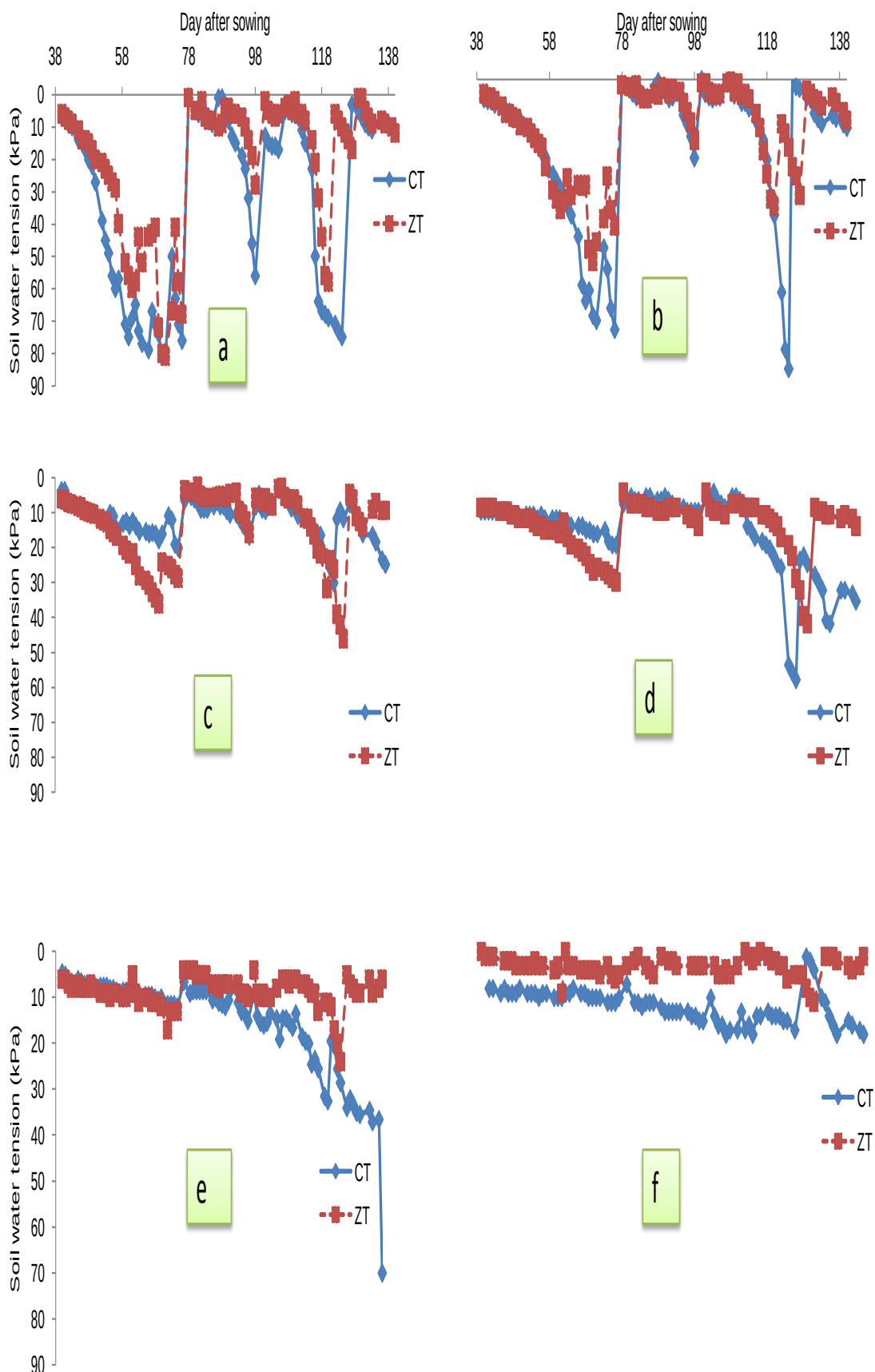


Fig. 4.10 Soil matrix potential at (a) 10, (b) 20, (c) 30, (d) 45, (e) 60 and (f) 90 cm soil depth in relation to conventional and zero tillage in wheat during 2012-13

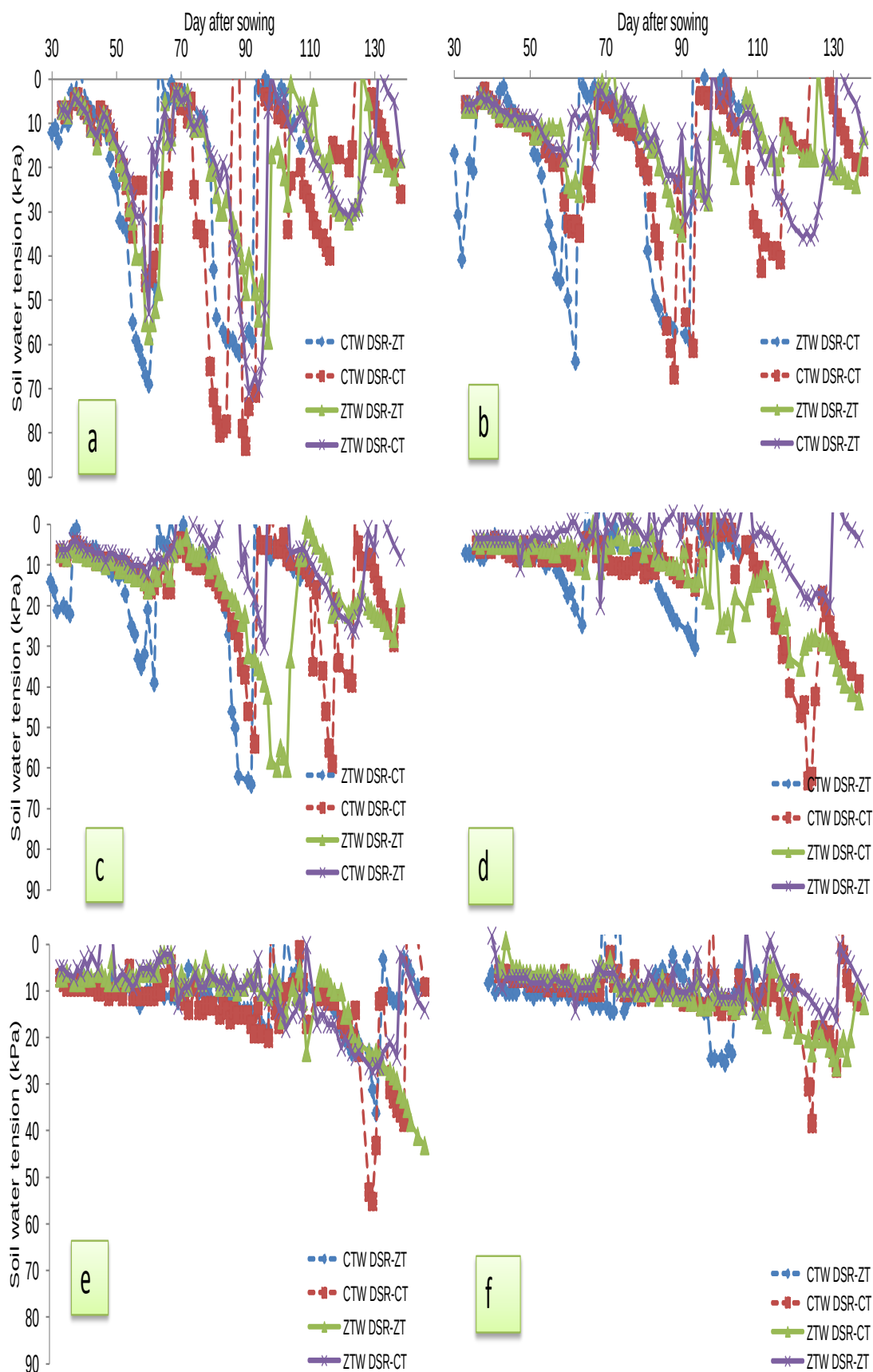


Fig. 4.11 Soil matric potential at (a) 10, (b) 20, (c) 30, (d) 45, (e) 60 and (f) 90 cm soil depth in relation to conventional and zero tillage in wheat during 2013-14

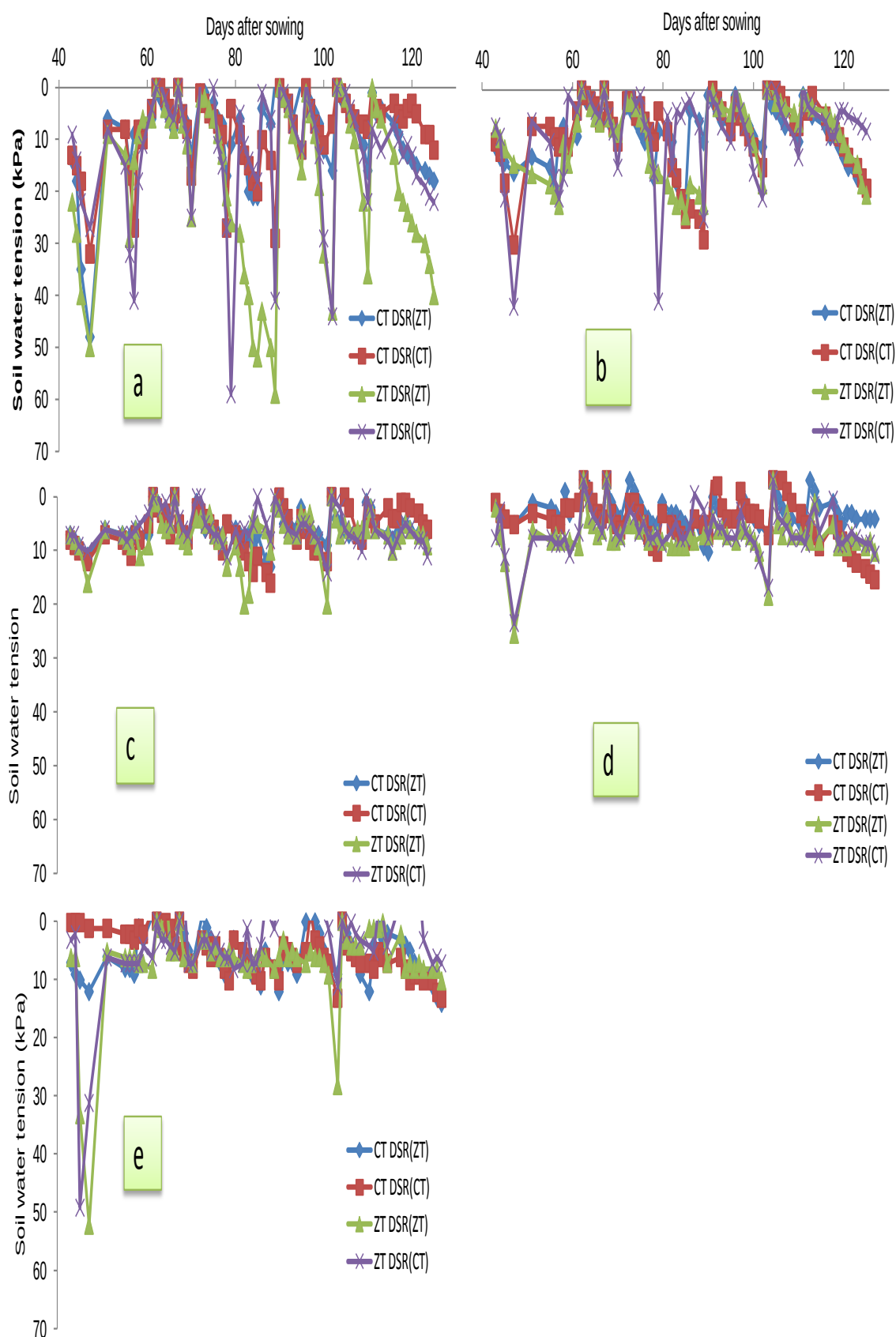


Fig. 4.12 Soil matrix potential at (a) 10, (b) 15, (c) 30, (d) 45 and (e) 60 soil depth in relation to conventional and zero tillage in rice 2013

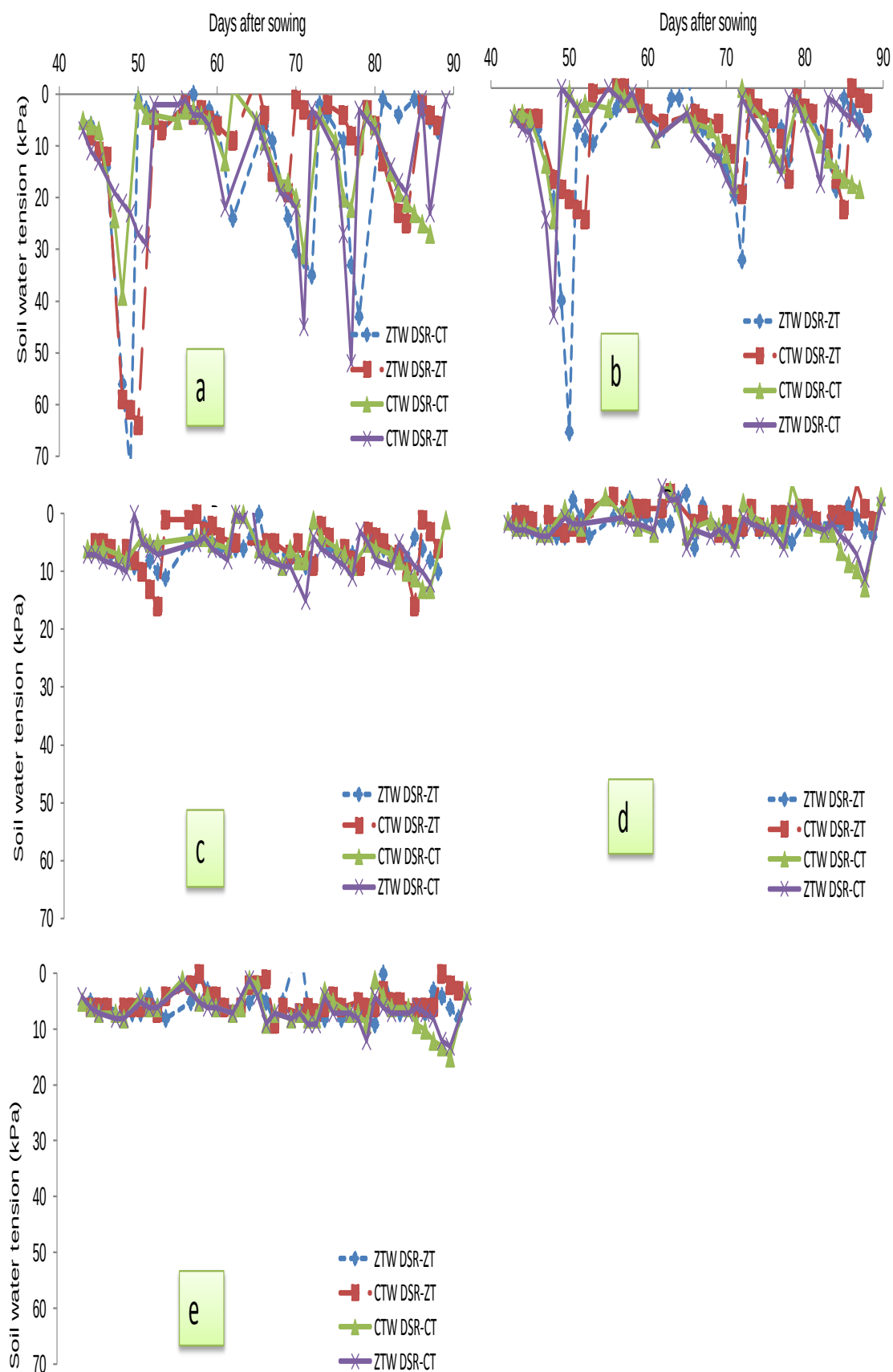


Fig. 4.13 Soil matrix potential at (a) 10, (b) 15, (c) 30, (d) 45 and (e) 60 soil depth in relation to conventional and zero tillage in rice 2014

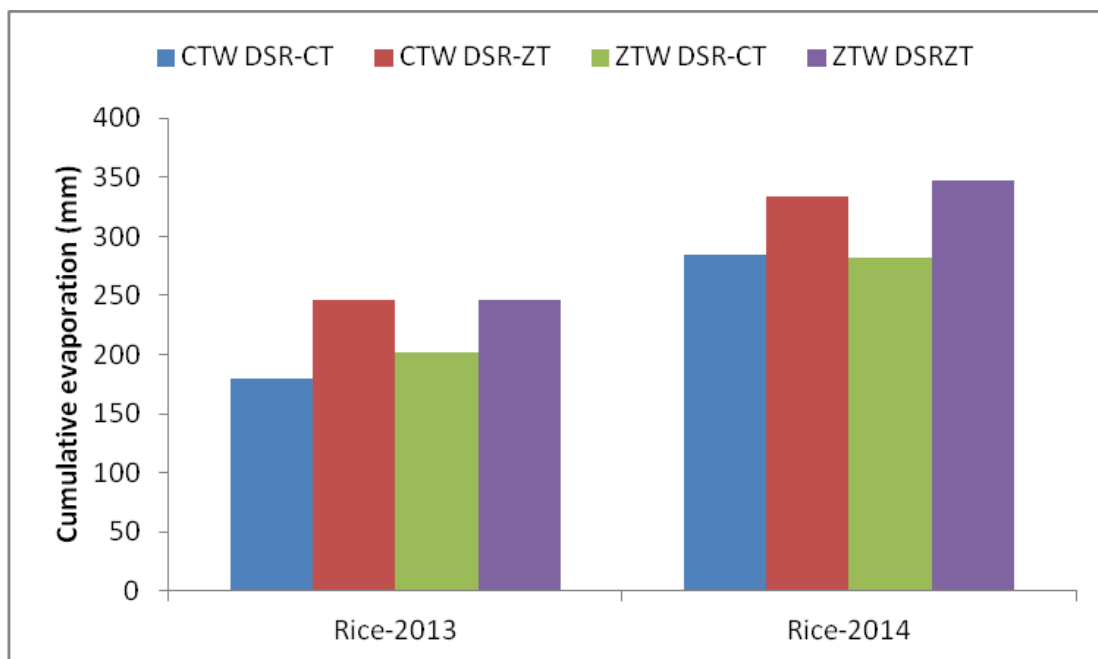


Fig. 4.14 Evaporation losses under different tillage scenarios in rice during 2013-2014.

4.2.3.3 Intervening period between wheat and rice

The soil matric potential profiles recorded immediately after wheat harvest till rice sowing (Fig. 4.15 and 4.16) clearly indicate that zero-till plots dried at a faster rate compared to the conventionally tilled plots during the period in 2013 and 2014. The drying was higher (28 per cent) in 10 cm soil layer (Fig. 4.15a) than in 20 and 30 cm soil (18 per cent) during 2013 (Fig. 4.15 b, c).

The corresponding values during 2014 were 21 per cent at 10 cm soil depth (Fig. 4.16 a) compared to 16-17 per cent in lower soil layers (Fig. 4.16 b, c). This is further substantiated by higher evaporation throughout the period when the cumulative evaporation was 7.6 per cent higher during 2013 (Fig. 4.17a) and 12.8 per cent during 2014 (Fig. 4.17b) in ZTW plots than in CTW plots during intervening periods. In 2014, the soil matric potential fluctuate during intervening periods after wheat harvest due to the four rain events occurring during this period.

In general, the zero tilled plots (without straw load) had higher soil temperature, soil matric potential, higher evaporation losses during the intervening periods after wheat harvest.

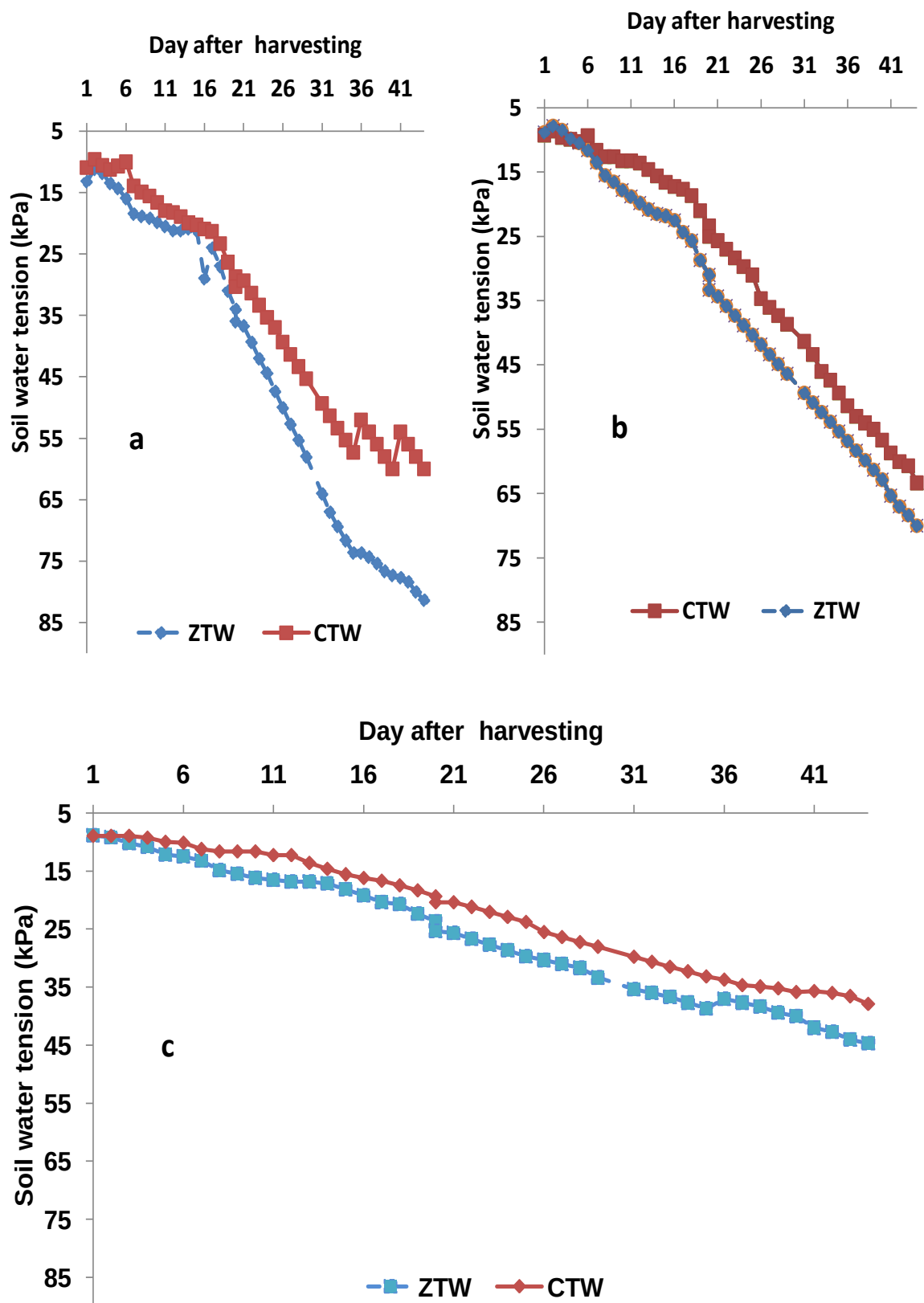


Fig. 4.15 Soil matrix potential as affected by tillage treatments during the intervening period during 2013 between wheat and rice at (a) 10 cm , (b) 20 cm and (c) 30 soil depths

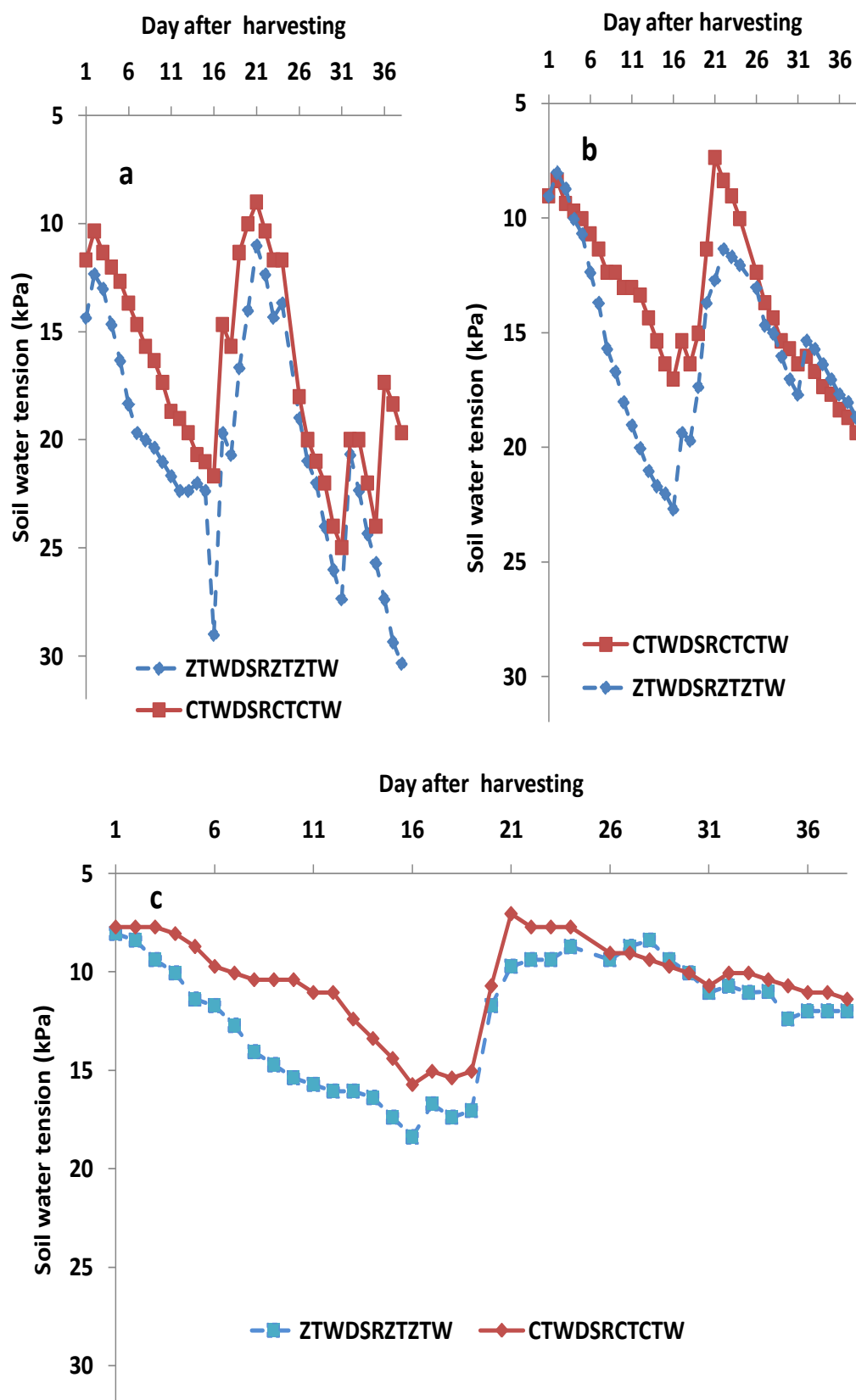


Fig. 4.16 Soil matrix potential as affected by tillage treatments during the intervening period during 2014 between wheat and rice at (a) 10 cm , (b) 20 cm and (c) 30 soil depths.

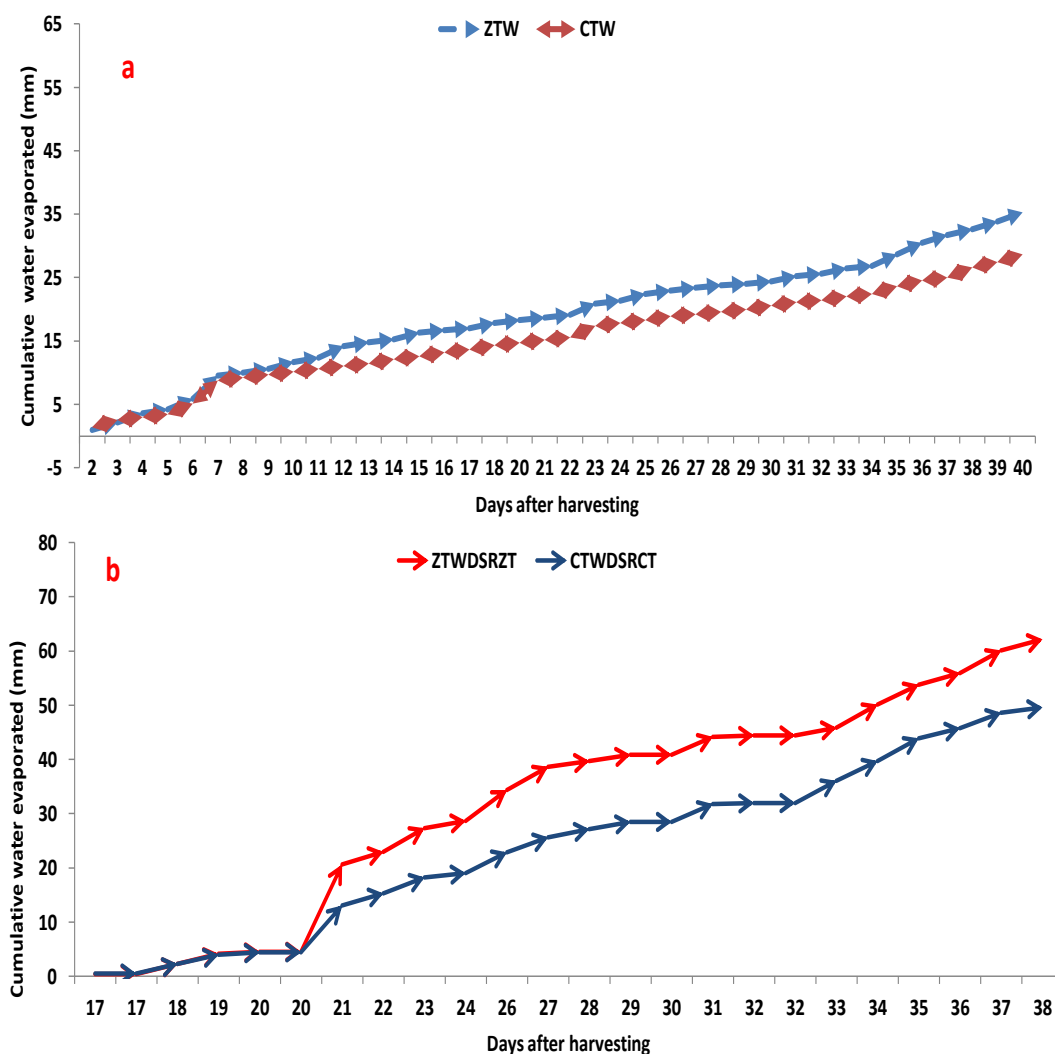


Fig. 4.17 Cumulative evaporation losses (mm) during intervening period after wheat harvest during (a) 2012-13 and (b) 2013-14

4.3 SOIL PHYSICAL ENVIRONMENT IN RELATION TO DOUBLE ZERO TILL SYSTEM

4.3.1 Bulk density

No significant effect of double zero tillage was observed on the bulk density throughout the soil profile up to 150 cm (Table 4.9) though surface soil (0-15 cm) showed some increment in soil bulk density. However, contrary to our study, Jat *et al* (2009) after two years of rice-wheat cultivation reported that double zero till (ZTDSR-ZTW) plots had significantly higher bulk density in the 0–5 and 5–10 cm soil layers when compared with other tillage systems, whereas it was higher under conventional-tillage (PTR-CTW and CTDSR-CTW) in 10–15 and 15–20-cm soil layers.

4.3.2 Soil moisture retention

No significant effect of double zero tillage was observed on the soil moisture retention throughout the soil profile up to 150 cm as compared to the plots under conventional

system (CTW-DSRP) (Table 4.9). The moisture content both at field capacity (0.3 bar) and permanent wilting point (15 bar) were similar after 2 years of double zero till (four cropping seasons) to the initial values recorded at the start of the experiment in 2012. The soil organic carbon analyzed in soil samples taken after four cropping season of zero tillage remained unchanged from the initial values measured at the start of the experiment. The effect of conservation technologies on soil physical characteristics may not be realized after 2–3 years of adoption of CA based component technologies.

Table 4.9 Soil bulk density and moisture retention as affected by four cropping seasons of zero-tillage in wheat-rice system

Soil Depths (cm)	Bulk Density (Mg m ⁻³)		Moisture content (% w/w) at 0.3 bar (Field Capacity)		Moisture content (%w/w) at 15 bar (Permanent wilting point)	
	2012	2014	2012	2014	2012	2014
0-15	1.66	1.68	11.3	11.4	7.7	7.8
15-30	1.74	1.73	10.4	10.5	6.2	6.1
30-60	1.59	1.59	12.1	12.1	6.4	6.3
60-90	1.63	1.62	11.3	11.4	6.7	6.7
90-120	1.57	1.58	12.1	12.0	7.3	7.4
120-150	1.61	1.60	12.5	12.6	6.6	6.6

4.3.3 Infiltration

The infiltration rate after four cropping seasons of zero tillage did not show any change (Fig. 4.18a) from that observed at the start of the experiment in 2012. The cumulative infiltration also was similar to the initial values recorded at the start of the experiment (Fig. 4.18b). Jat *et al* (2009) reported the similar infiltration rates in double zero till plots and the plots under CTW-PTR.

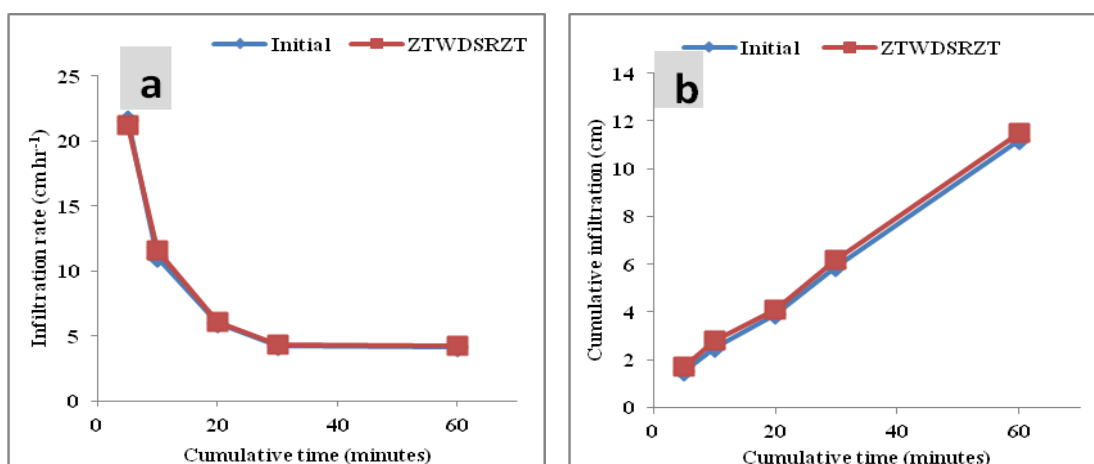


Fig. 4.18 Effect of four cropping seasons of zero tillage on the (a) infiltration rate and (b) cumulative infiltration as compared to the conventional system

4.3.4 Hydraulic conductivity

Hydraulic conductivity (cm s^{-1}) is an important soil physical property and indicated the water intake conduction behaviour of the soil. During the current investigation hydraulic conductivities (both saturated and un-saturated) of the sandy loam soil reported to have non-significant effect by the double zero till viz. ZTW-DSRZT during the last four cropping seasons and it's range remain almost similar to that in the conventional system of rice-wheat establishment (Fig 4.19).

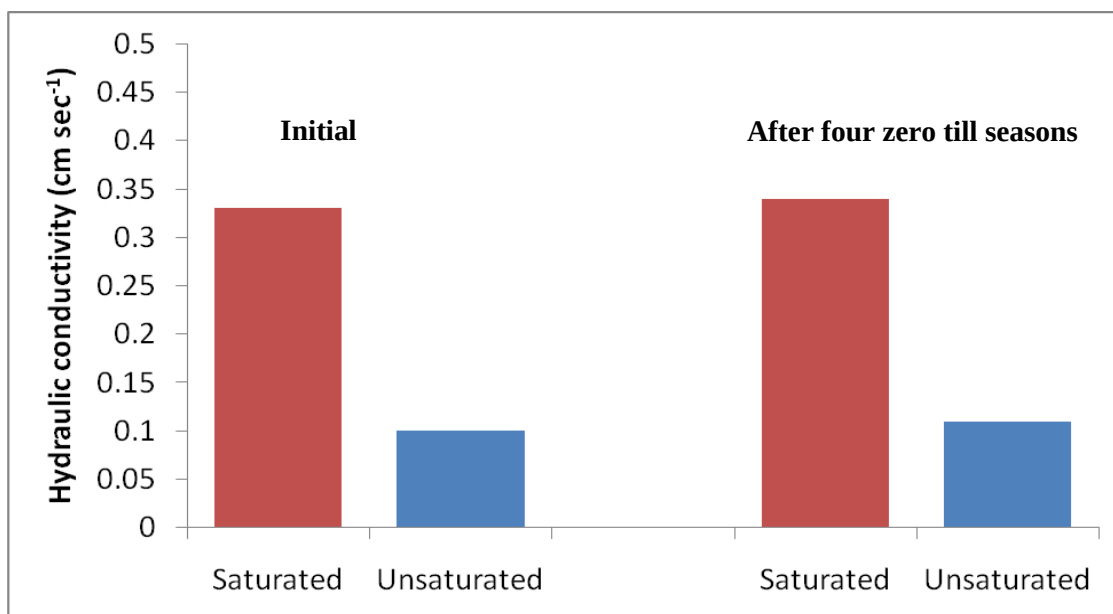


Fig. 4.19 Saturated and unsaturated hydraulic conductivity as affected by conservation tillage after four cropping seasons

4.3.5 Aggregation

The water stable aggregates in each size class were recorded after four cropping seasons of zero tillage in wheat-rice cropping system were similar to those observed at the start of the experiment (Table 4.10).

Table 4.10 Distribution of water stable aggregates in relation to four cropping seasons of zero tillage

Sieve size (mm)	per cent soil aggregates	
	Initial Status	ZTW-DSRZT
> 2.0	61.9	62.0
2.0-1.0	2.80	2.78
1.0-0.5	1.65	1.64
0.5-0.25	8.98	8.96
0.25-0.10	4.62	4.60
< 0.10	20.1	20.1

The mean weight diameter of water stable aggregates measured in 2014 was also similar to that measured at the start of the experiment in 2012 (Fig. 4.20).

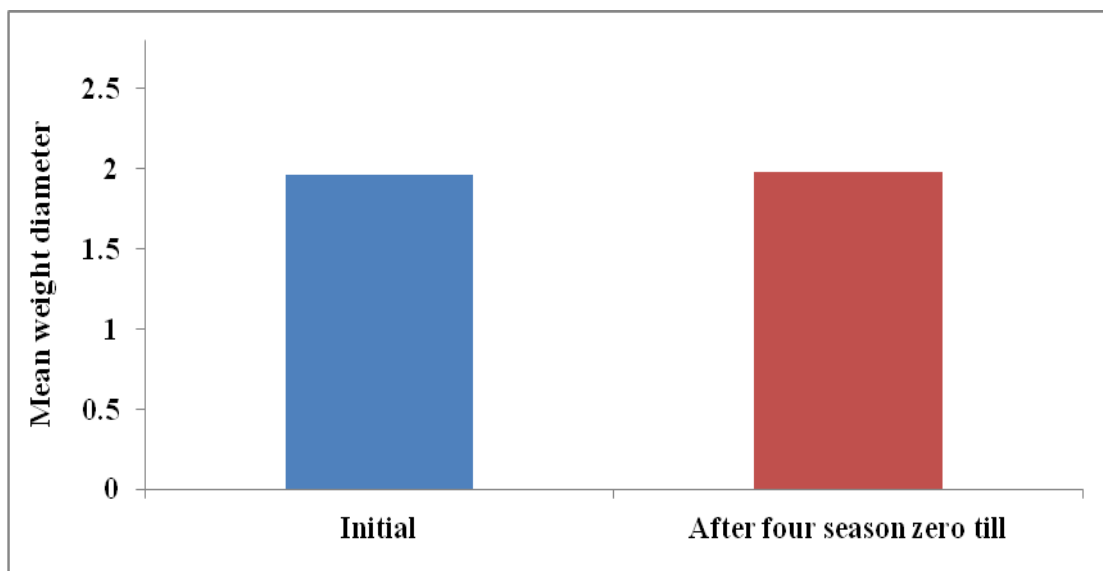


Fig. 4.20 Mean weight diameter as affected by four seasons zero till plots

4.3.6 Soil temperature

The soil temperature of 0-5 cm soil layer (during wheat season) recorded during peak hours (1400 hrs) lower in plots under double zero-till system throughout the growing period (30-140 DAS) as compared to the conventional tillage system. The difference was much more pronounced during during 90-140 DAS (Fig. 4.21a). The plots with zero tillage in wheat recorded lower soil temperatures and presence of mulch @ 4.4 t ha⁻¹ on the soil surface might be responsible for lower temperate.

The soil temperature of 0-5 cm did not observe any trend, perhaps due to frequent irrigations in rice (Fig. 4.21b). The soil temperature profiles during the intervening period after wheat harvest till sowing of rice (Fig. 4.22a,b) show that the temperature remained higher in zero-till plots compared to the conventional till plots during both the years except when the rains occurred. After rains during 2014, the soil temperature under both the tillage systems was similar (Fig. 4.22b)

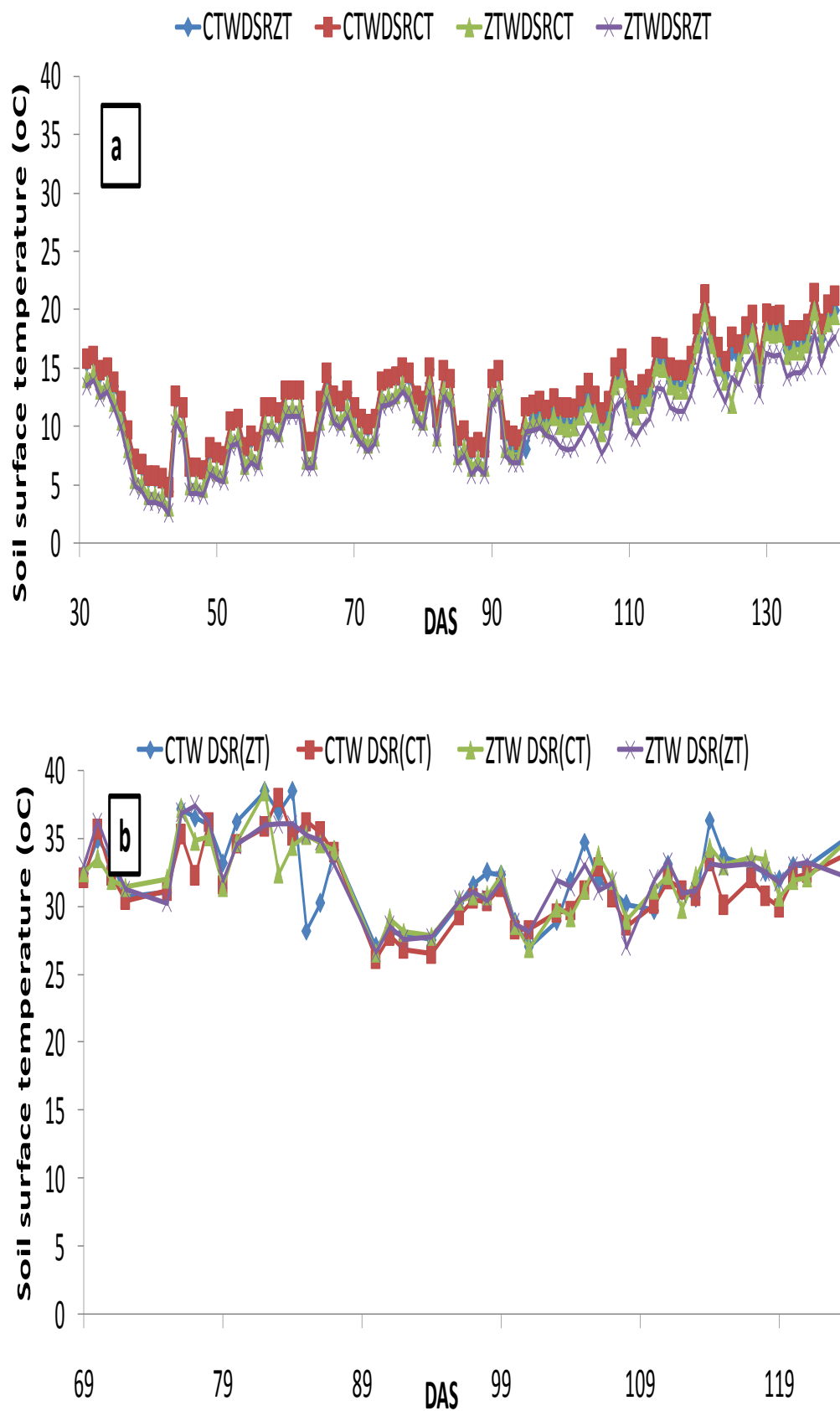


Fig. 4.21 Soil surface temperature fluctuations as affected by different tillage methods during 2013-14 (a) wheat and (b) rice

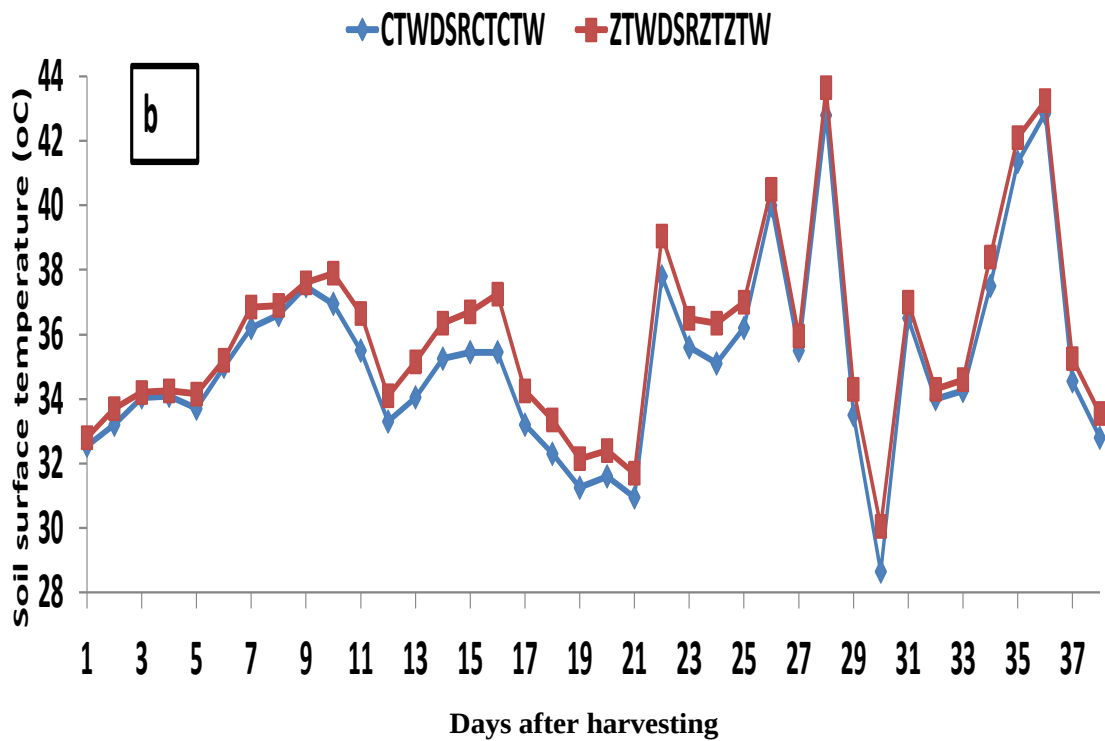
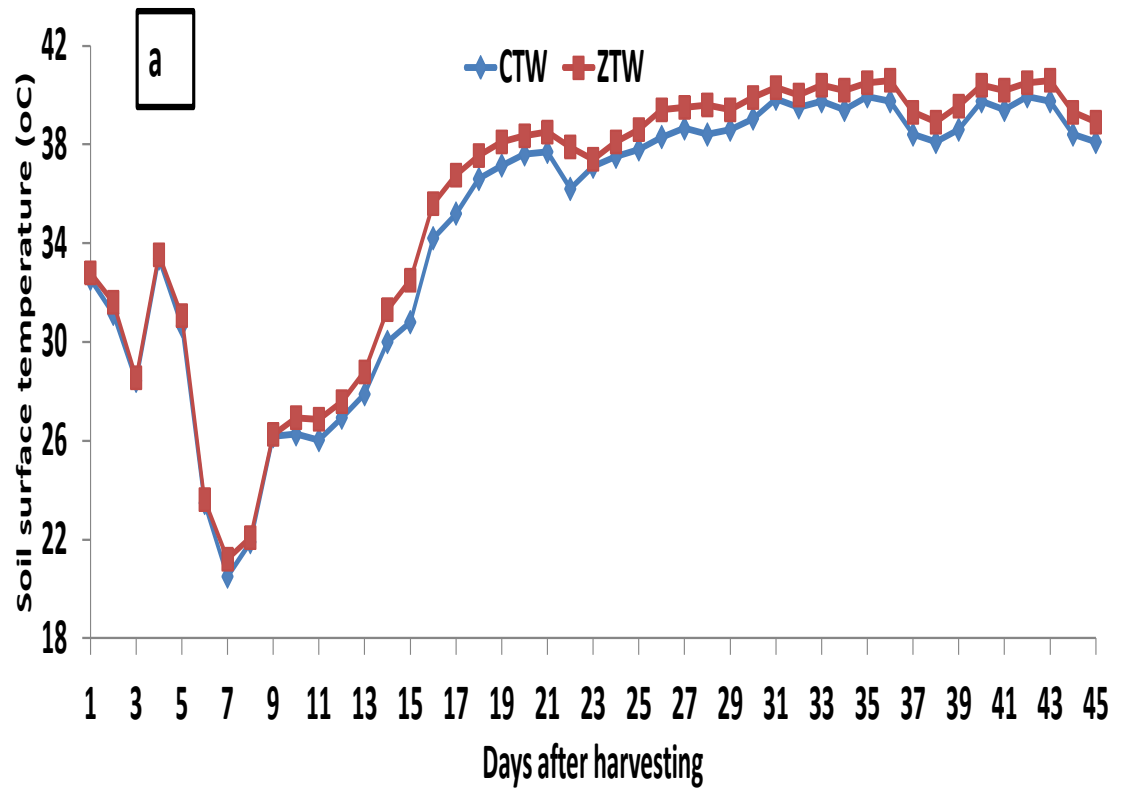


Fig. 4.22 Soil surface temperature fluctuations as affected by different tillage methods during intervening periods after wheat during (a) 2012-13 and (b) 2013-14

CHAPTER V

SUMMARY

Wheat-rice cropping system in north-west India, particularly in Punjab has taken a toll on the natural resources of air, water and soil. Several resource conservation technologies viz. zero tillage in wheat, direct seeding and mechanical transplanting of rice under different tillage conditions, being advocated in the region, have been studied under isolated conditions for individual crops and are shown to be resource conserving techniques. However, these technologies need to be studied for complete wheat-rice cropping system in the region.

Field experiments were conducted during 2012-14 with the following objectives:

- ❖ To study the crop performance and water productivities of rice-wheat system under different establishment methods
- ❖ To compute water balance of rice-wheat system under different establishment methods
- ❖ To study the impact of double zero till system in rice-wheat system on soil physical environment and soil water dynamics

The treatments consisted of zero (ZTW) and conventional (CTW) tillage as main plot, establishment method of direct seeded (DSR) and mechanical transplanted rice (MTR) as sub plot and tillage in rice viz. puddle (P), conventional till (CT) and zero till (ZT) as sub-sub treatments in split-split plot design. The treatments, replicated thrice, were laid in split-split plot design. The wheat and rice crops were raised as per the recommended practices of Punjab Agricultural University, Ludhiana. The results so obtained are being summarized as below:

The wheat biomass in ZTW plots during 2012-13 was slightly lower than that in CTW plots till 110 DAS but later on the biomass was higher in ZTW plots than in the CTW plots while, it was similar in ZTW and CTW plots throughout the crop season during 2013-14. The tiller density of wheat was initially higher in CTW than in ZTW plots during both the years but it became similar during the later growth. The leaf area index (LAI) of wheat was higher in CTW than in ZTW plots at all the crop stages during both the years but was statistically similar with respect to establishment method and tillage in rice. The yield attributes of wheat viz. grains per panicle, average grain weight and harvest index were not affected significantly by tillage in wheat, establishment method and tillage in rice. The grain yield of wheat was higher in 2013-14 than in 2012-13 while CTW and ZTW plots had similar yields during both the years. The establishment method and tillage in rice did not affect the wheat grain yield significantly during 2013-14, though it was slightly higher in CTW than in ZTW plots.

The biomass of rice was higher in CTW than in ZTW plots during 2013 but it was similar in the two treatments during 2014. The establishment method of rice significantly affected the crop biomass, being higher in DSR than in MTR plots during both the years. The

average crop biomass was significantly lower in zero-till rice than in puddle and CT plots, irrespective of the establishment method during both the years. The tiller density was not affected significantly by tillage in wheat during both the years. The effective tillers were similar with respect to tillage in rice during both the years. The LAI was slightly higher in CTW than in ZTW plots throughout the growing season during 2013 and 2014. The establishment method significantly affected the LAI throughout the crop growth during both the years, being higher by 50 per cent at all the crop growth stages in DSR than in MTR plots in 2013, the difference increased to 115 per cent during 2014. The tillage in rice significantly affected the LAI, being higher in puddle than in CT and ZT plots at 106 DAS during 2014.

The DSR plots on an average had 10.1 and 15.9 per cent higher floret fertility during 2013 and 2014, respectively, than in MTR plots. The fertility percentage was highest in puddle followed by CT and lowest in ZT plots, the differences being significant in 2013. In 2014, the puddle and CT plots had similar fertility percentage which was significantly higher than that in ZT plots. The average grain weight of rice was significantly higher in CTW than in ZTW plots during 2014, while in 2013 it was similar in the two treatments, while DSR and MTR plots had similar average grain weight during both the years. The tillage in rice significantly affected the average rice grain weight, being highest in puddle, followed by CT and lowest in ZT plots both under DSR and MTR. The average grain weight in 2014 was higher in puddle and CT plots of DSR as compared to MTR plots, whereas in ZT plots, the establishment method did not affect the average grain weight.

The grain yield of rice was higher in CTW than in ZTW plots, the differences being statistically significant during 2014. The grain yield of DSR was similar to that of MTR during 2013 but was significantly higher than MTR during 2014. The tillage in rice significantly affected the grain yield in the order puddle > dry tilled > zero till plots during both the years. The average grain yield decreased by 17.2 per cent in 2013 and 27.7 per cent in 2014 in CT plots from that in puddle plots. It further decreased by 24.4 and 28.4 per cent in ZT plots, respectively.

The land productivity of wheat-rice cropping system was 15.8 and 11.3 per cent higher in CTW than in ZTW plots during 2012-13 and 2013-14, respectively. The tillage in rice significantly affected total land productivity in both the years, being highest in puddle followed by CT and lowest in ZT plots. The land productivity of the cropping system was highest CTW-DSR-P and lowest under ZTW-MT-ZT scenario, while irrigation water productivity of the system was highest in CTW-MT-P and lowest in ZTW-DSR-ZT scenario.

The irrigation water productivity (WP_i) of wheat was significantly lower in ZTW (1.81 g kg^{-1}) than in the CTW plots (2.16 g kg^{-1}) during 2012-13. However, it was similar in the two treatments during 2013-14. The average WP_i of wheat was similar in puddled and CT

plots of rice but was significantly higher in ZT plots. The average WP_1 of rice was higher in CTW than in ZTW plots during both the years, the differences being significant during 2014. The WP_1 of MTR was 31.1 per cent higher in CTW than in ZTW plots compared to 9.5 per cent during 2013. The mean WP_1 was 15 per cent higher in CTW than in ZTW plots during 2014. The average WP_1 of MTR was significantly higher than that of DSR during both the years. The WP_1 of rice in puddle, CT and ZT plots was similar in 2013 but the differences became significant during 2014. It was sufficiently higher in puddle (0.56 g kg^{-1}) than in CT (0.29 g kg^{-1}) and ZT (0.25 g kg^{-1}) plots. The WP_1 was higher by 48.9 per cent in puddle, 32 per cent in CT and 38.1 per cent in ZT plots of MTR than in DSR in 2014.

The WP_1 of wheat-rice cropping system was significantly higher (16-19.5 per cent) in CTW than in ZTW plots during 2012-14. The establishment method of rice significantly affected the WP_1 of the cropping system, being higher in MTR ($0.81\text{-}0.88 \text{ g kg}^{-1}$) than in DSR ($0.60\text{-}0.77 \text{ g kg}^{-1}$) plots. The tillage in rice significantly affected WP_1 of the cropping system during both the years. The WP_1 of wheat-rice cropping system, though similar in CT (0.76 g kg^{-1}) and ZT (0.71 g kg^{-1}) plots of rice during 2012 -13, was 11.2 per cent lower in ZT plots during 2013-14. The decrease in system WP_1 in 2012-13 due to zero tillage in wheat was highest (18.4 per cent) in puddle plots, followed by 15.7 per cent in CT and lowest (9.8 per cent) in ZT plots of rice. Similar was the trend during 2013-14. The irrigation water productivity (WP_1) of wheat-rice cropping system increased in the order $ZTW\text{-}DSR\text{-}ZT < CTW\text{-}DSR\text{-}ZT < ZTW\text{-}MTR\text{-}CT < ZTW\text{-}DSR\text{-}P < CTW\text{-}DSR\text{-}P < ZTW\text{-}MT\text{-}P < CTW\text{-}MT\text{-}P$.

The irrigation water consumption during wheat in 2013-14 was similar (331–348 mm) to that in 2012-13 (334-353 mm). It was similar in ZTW and CTW plots in 2013-14 except in double zero-till plots (ZTW-DSRZT). The change in profile moisture was higher (61.6-78.2 mm) in 2012-13 than in 2013-14 (42.5-54.5 mm). In 2013-14, the effect of ZT in DSR was more pronounced in affecting $\Delta\theta$, being 42.5-47.1 mm in DSR-ZT plots in comparison to 54.3-54.5 mm in DSR-CT plots. The evapo-transpiration (ET) of wheat during 2012-13 was slightly higher (430-433 mm) to that in 2013-14 (401-430 mm).

The irrigation water use in rice was sufficiently higher during 2014 than in 2013 (1526-1651 mm) with 323 mm of rainfall split over 17 wet days compared to that in 2013 (991-1021 mm) with 462 mm rain spread over 16 storms. The change in profile moisture storage during rice was not so conspicuous as in wheat, perhaps due to frequent irrigations during rice season as compared to wheat season. The lower seepage losses were recorded during 2013 (265-462 mm) as compared to 2014 (561-732 mm). In double ZT system viz. ZTW-DSRZT, seepage was higher (35.7 per cent during 2013 and 16.4 per cent during 2014) as compared to the conventional system viz. CTW-DSRCT. Zero tillage in wheat increased

seepage losses in DSR under both ZT and CT conditions. The deep drainage beyond 60 cm was to the extent of 36-54 per cent of total input water used during the crop season. During both the years, the deep drainage losses were lower in plots under zero tillage in wheat but zero tillage in DSR resulted in higher deep drainage losses. The evapo-transpiration losses in rice 2014 were higher (497-532 mm) than in 2013 (392-399 mm). However, the ET losses of DSR were not affected by tillage both in rice and wheat. The ET constituted 27 per cent of the total input water used during both the years.

The total input water for wheat-rice cropping system was higher (2330-2467 mm) during 2014 compared to 1955-1993 mm during 2013. The deep drainage of the system during 2012-13 was 40 per cent of the total input water used in the CTW plots with DSR-CT as compared to 30.4 per cent in ZTW plots. The corresponding values during 2013-14 were 33.8 per cent (CTW) and 28.7 per cent (ZTW), respectively. Similar was the trend in case of DSR-ZT. Zero tillage in wheat resulted in higher seepage losses (462-732 mm) compared to conventional tillage (284-561 mm) during both the years. The evapo-transpiration (ET) losses of the wheat-rice cropping system were higher during 2013-14 (971-1057 mm) as compared to 2012-13 (908-922 mm), which was due to the higher amount of rain (39 per cent) during 2012-13. However, the ET losses of wheat-rice cropping system including the intervening period were not affected by tillage in wheat or tillage in rice.

The irrigation water productivity (WP_I) of wheat-rice cropping system ranged from 0.56-0.74 g kg⁻¹ in 2012-13 compared to 0.45-0.54 g kg⁻¹ during 2013-14. Zero tillage in wheat resulted in lower (18 per cent) WP_I compared to the conventional system viz. CTW-DSRCT during 2012-13. This difference decreased to 13 per cent during 2013-14. The input water productivity (WP_{I+R}) of wheat-rice cropping system decreased by 34.2 per cent in 2012-13 while shifting from complete conventional tillage system to complete zero tillage system. However, this difference decreased to 22.2 per cent in 2013-14. The real water productivity ranged from 0.83-1.08 g kg⁻¹ in 2012-13 to 0.86-1.02 g kg⁻¹ during 2013-14. Among the different tillage scenarios, irrigation (WP_I), total input (WP_{I+R}) and evapo-transpiration (WP_{ET}) based water productivity followed the order CTW-DSRCT > ZTW-DSRCT > CTW-DSRZT > ZTW-DSRZT.

Soil physical environment was not affected by double zero till practised over the two years (four cropping seasons). The bulk density, infiltration rate, mean weight diameter, soil water retention and hydraulic conductivities (saturated and un-saturated) were not significantly affected by zero tillage in either or both the crops. In general, the zero tilled plots were observed to be wetter than conventionally tilled plots at all the soil depths (0-120 cm) during wheat season, whereas during rice season, the conventional tillage resulted in lesser drying of the soil profile (0-60 cm) than zero tilled plots.

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Fig. 3.4 Different field operations carried out during the experiment viz. (a) disking, (b) ploughing, (c) planking, (d) calibration of seed drill, (e) sowing in conventionally tilled and in (f) zero tilled plots



Fig. 3.5 Different field operations carried out during the experiment viz. (a) puddling with power tiller, (b&d) wet seeding with drum seeder, (c) mechanical transplanting in zero tilled, (e) conventionally tilled and (f) puddled plots



Fig. 3.6 Rice crop under different establishment and tillage methods viz. (a) direct wet seeded rice, (b) CT-direct dry seeded rice, (c) ZT-direct dry seeded rice, (d) puddled mechanically transplanted, (e) CT-mechanically transplanted and (f) ZT-mechanically transplanted rice



Fig. 3.7 Installation and measurement procedure for mini lysimeters (a) filling of lysimeter, (b) lifting of filled lysimeter using chain-pulley arrangement, (c) filled lysimeter, (d) weighing of lysimeter



Fig. 3.8 Installation and measurement procedure of (a) tensiometers, (b) water filling and cork fixing, (c-e) tensiometers, (f) Soil-spec measuring tension readings

SUBMITTED/ACCEPTED/PUBLISHED RESEARCH ARTICLES

S. no.	Publication	Name of the journal	NAAS rating	Status
1	Tillage and establishment method impacts on land and irrigation water productivity of wheat-rice system in north-west India	Soil and Tillage Research	8.58	Submitted
2	Soil water balance and water productivity of wheat-direct dry seeded rice cropping system under conventional and zero-till conditions in semi-arid tropics of India	Agronomy for Sustainable Development	8.84	Submitted
3	Tillage residual effects on soil moisture dynamics after wheat during intervening period of rice-wheat sequence in South-Asia	Green Farming	4.79	Accepted
4	Soil physical environment as affected by double zero tillage in rice wheat cropping system of North-West India	An Asian Journal of Soil Science	3.19	Accepted
5	Soil moisture dynamics during intervening period in rice-wheat sequence as affected by different tillage methods at Ludhiana, Punjab, India	Soil and Environment (Pakistan Journal of Soil Sciences)	4.50	Published

Title of the manuscript

**Tillage and establishment method impacts on land and irrigation
water productivity of wheat-rice system in north-west India**

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Tillage and establishment method impacts on land and irrigation water productivity of wheat-rice system in north-west India

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Abstract: The sustainability of wheat-rice production system in north-west (NW) Indo-Gangetic Plains (IGP) of India is being threatened primarily due to the scarcity of water and labour, degradation of soil health and changing climatic conditions. The resource conservation technologies (RCTs) being advocated for countering these threats in the region have been evaluated mostly for the individual crops, without depicting the impact of these technologies on the succeeding or preceding crop. A study was thus conducted during 2012-2014 in NW India to assess the land and irrigation water productivity of wheat-rice cropping system under different establishment and conservation tillage techniques in a sandy-loam soil (coarse loamy, calcareous, mixed, hyperthermic Typic Ustochrept). The treatments included zero (ZTW) and conventional (CTW) tillage in wheat as main plot, establishment methods (direct seeded (DSR) and mechanically transplanted rice (MTR) as sub-plot and tillage in rice viz. puddle (P), dry (CT) and zero (ZT) tillage as sub-sub plot treatments, replicated thrice in split-split plot design.

The performance of wheat with conventional tillage was statistically similar to that with zero tillage during both the years. The productivity of wheat-rice cropping system however, was significantly lower in ZTW plots than in CTW plots. The residual effect of tillage in wheat on rice productivity was distinct during the second year of study, when the CTW plots recorded significantly higher (17.5%) rice yield than the ZTW plots. The direct seeded rice yielded higher than the mechanically transplanted rice during both the years, the differences being significant during 2014. The productivity of the cropping system with DSR was statistically similar to that with MTR. The puddle rice performed significantly better than CT and ZT rice during both the years. The irrigation water productivity (WP_I) of wheat-rice cropping system increased in the order $ZTW-DSR-ZT < CTW-DSR-ZT < ZTW-MTR-CT < ZTW-DSR-P < CTW-DSR-P < ZTW-MT-P < CTW-MT-P$.

Key words: Direct-seeded rice; Indo-Gangetic Plains; mechanically transplanted rice; puddling; zero-tillage

1. Introduction

The wheat-rice cropping system (RWCS), spread over 13.5 m ha in the Indo-Gangetic Plains (IGP) of India, Bangladesh, Nepal and Pakistan (FAOSTAT, 2010),

is fundamental to the employment, income, food security and livelihood for millions. In India, this cropping system occupies 10.5 m ha and contributes about 40% of the country's total food grain basket (Saharawat et al., 2010) and provides staple grains for nearly 42% of the total population of 1.3 billion in South Asia (Jat et al., 2005). However, the productivity and sustainability of the system are threatened mainly due to the increasing scarcity of water and labor (Erenstein, 2011; Gathala et al., 2011). The problem is further intensified by the planners and policymakers favouring highly subsidised power and irrigation water, leading to overuse of these resources (Naresh et al., 2013) and hence drastic fall in ground water levels. Moreover, the degrading soil health in terms of the soil physical environment is further accentuating the problem.

The RWCS with conventional practices has led to continued exploitation of the natural resources (Hira , 2004; Bhatt and Kukal, 2014; Bhatt and Kukal, 2015) in the region which has further put extra pressure on energy requirements (Hira, 2009). The per capita availability of water in many Asian countries has declined by 40-60% which is further expected to decline further by 15-54% in the coming 35 years (Gleick, 1993). By 2025, 15-20 million ha of rice land is expected to suffer due to some degree of water scarcity (Tuong and Bouman, 2003). This scarcity is expected to be more severe in populous countries like India.

Conventionally, rice is established in puddle (P) soils with heavy water and labor inputs (Dawe, 2005), while negative effects of puddling through structural degradation on upland crops are of concern (Aggarwal et al., 1995; Kukal and Aggarwal, 2003a). Repeated puddling of coarse and medium textured soils has led to sub-surface compaction (Sur et al.,1981; Kukal and Aggarwal, 2003a) which is proving to be detrimental for upland crops like wheat due to aeration stress (Kukal and Aggarwal, 2003b). The scarcity of labor is becoming a global phenomenon and could threaten the sustainability of conventional RWCS in near future (Rashid et al., 2009; Kumar and Ladha, 2011). Thus conventional puddle transplanted system of rice cultivation is water-, capital- and energy-intensive. On the other hand wheat, conventionally grown in upland well-drained soils after complete burning of rice residues (120 million tons) and repeated tillage operations leads to environmental pollution besides depriving the soils of a huge amount of nutrients and organic carbon.

Various resource conservation technologies (RCTs) viz. direct drilling of wheat seeds with and without crop residues, direct seeded rice, mechanical transplanting of rice in conventional and zero till conditions, etc are being advocated for increased productivity, sustainability and profitability of RWCS as these primarily focus on conservation tillage and recycling of crop residues (Singh et al., 2011; Bhatt and Khera, 2006; Hobbs et al., 2008). Isolated studies (Rajesus et al., 2011) involving individual crops have indicated improved water productivities, which are seldom based on systematic measurements of water balance components of crops grown with these RCTs (Humphreys et al., 2010; Kukal et al., 2014). The magnitude of the benefits of RCTs tends to be site-and situation-specific and cannot be generalized across the farming systems in different agro-climatic regions (Humphreys et al., 2010; Sudhir-Yadav et al., 2011; Sudhir-Yadav et al., 2014). Moreover, the impact of RCTs with respect to establishment and tillage techniques on land and water productivity of the cropping system as a whole is not well documented in the literature (Devkotaa et al., 2015; Jat et al., 2014). The use of these RCTs in one crop may affect the performance of other crop in the cropping system and/or negate the impacts in the cropping system as observed in the individual crop. The present study was thus conducted to assess the impact of establishment techniques coupled with conservation tillage in wheat and rice on land and irrigation water productivity of wheat-rice system in north-west Indo-Gangetic Plains of India.

2. Material and methods

2.1 Site description

The field experiments were carried out at the research farm (30°54'N, 75°98'E, 247 m above sea level) of Punjab Agricultural University, Ludhiana, India, during 2012-14. The experimental soil was sandy loam (sand 65-68%, clay 11-3%), neutral to slightly alkaline, non-saline and medium in soil organic carbon (0.44%) in the surface layer (Table 1). The soil had sub-surface compact layer (bulk density of 1.74 Mg m⁻³ at 15-30 cm). The available nutrients were in the medium range while moisture content (% g g⁻¹) on an average decreased to 71.5% from field capacity to permanent wilting point. The depth to the ground water at the site was around 24 m and the quality of water was good for all crops (Table 2). The experimental site was under puddle transplanted rice for the last 20 years except that the field was under direct dry-seeded rice (DSR-CT) sown under tilled conditions during the immediate

previous year (2012). The climate is subtropical with hot and dry summers (March-June), wet monsoon season (late June to mid-September) and a cool dry winter (October-February). The long-term average annual rainfall is 734 mm, 85% of which occurs during a short period of July-September.

2.2 Treatments and experimental design

Twelve combinations of different tillage and establishment methods were tested in the rice-wheat cropping sequence (Table 3). The treatments consisted of zero- (direct-drilling of wheat in standing stubbles of the previous crop, ZTW) and conventional-tillage (disked twice followed by 2 passes of tractor-drawn cultivator and one planking, CTW) for wheat in main plots (13.8 m x 25.1 m) with three replications in randomized block design. In the following rice crop, the main plots were split into two subplots for differential rice establishment viz. direct-seeded rice (DSR) and mechanically transplanted rice (MTR). These subplots were further split into three sub-sub plots of 49.7 m² (13.8 m×3.6 m) for differential tillage treatments in rice viz. puddle (P), dry and (CT) and zero-till (ZT). The tillage treatments in rice were randomly allocated in subplots of both DSR and MTR (Table 3).

2.3 Crop management

2.3.1 Wheat

The field was laser levelled prior to establishment of the experiment and a pre-sowing irrigation (PSI) was applied. The wheat was directly drilled into standing stubbles (4.4 t ha⁻¹) of the previous rice crop using Happy Seeder (a zero-till drill machine which cuts the standing rice stubbles on its way and sows the seeds in a single operation) (Yadvinder-Singh et al., 2009). The crop was sown at field capacity soil moisture in the first fortnight of November during both the years. For conventional tillage, the plots were disked twice with tractor-drawn disks to chop the stubbles followed by two passes of tractor-drawn cultivator at field capacity moisture content. Thereafter, the soil was planked with a wooden plank to create a fine layer of soil at the surface. The wheat cultivar PBW 621 was sown at a seed rate of 112 kg ha⁻¹ at row spacing of 20 cm. The diammonium phosphate (DAP) and muriate of potash (MOP) was applied @ 138 and 50 kg ha⁻¹, respectively, before cultivation in conventionally-tilled plots and placed by the side of the seed while drilling in zero-till plots. The nitrogen was applied as urea in two splits @ 113 kg ha⁻¹ at sowing and 30 days after sowing (DAS). The crop was harvested in the third week of April during both the years.

2.3.2 Rice

The rice crop was established as puddle (P), dry-till (DT) and zero-till (ZT) under both the establishment methods viz. direct-seeded and mechanical transplanting. The plots were puddled after dry pre-puddling tillage as done in case of wheat. The puddling comprised of two passes of hand-driven power tiller in ponded water. For direct seeding of rice in puddle soil, pre-germinated seeds were sown using drum seeder @ 40 kg ha⁻¹ at row spacing of 20 cm. The direct seeding of rice in CT and ZT plots was carried out in the same way as done in case of wheat. For mechanical transplanting, the 30-d old seedlings (sown at the same date as in DSR) were transplanted using mechanical transplanter at 30 cm x 17 cm spacing. All the plots were applied with 10 kg ZnSO₄ at the time of field preparation. The nitrogen was applied as urea in four splits in DSR (14, 28, 49 and 70 DAS) and three splits in MTR (5, 30 and 51 DAT). To manage iron deficiency, the crop was sprayed thrice at weekly interval with 1% FeSO₄ solution at 30 DAS/DAT.

2.4 Irrigation management

After a pre-sowing irrigation, the first common irrigation was applied to wheat at 28 DAS. Further irrigations were applied on the basis of soil matric potential of -35 kPa at 35 cm depth (S S Kukal, Personal Communication). The last irrigation to wheat crop was applied 15-20 days before the crop harvest.

In rice crop, the puddled plots were irrigated till 15 DAT to ensure ponded water conditions and thereafter, these were irrigated on the basis of soil matric potential of -15 kPa at 15-20 cm depth (Kukal et al., 2005). In dry till (CT) and zero till (ZT) plots of DSR, the irrigations were applied every alternate day till the establishment of the crop (25-30 DAS) and thereafter, the plots were irrigated on the basis of soil matric potential as mentioned above. In DT and ZT plots of MTR, the irrigations were applied every alternate day till 12-15 DAT for ensuring the efficacy of the applied herbicides and thereafter, the crop was irrigated on the basis of soil matric potential as mentioned above.

2.5 Weed and insect-pest management

In ZT wheat plots, the weeds were managed prior to seeding by spraying glyphosate @ 1 l ha⁻¹ while no herbicide was used in CT plots before seeding. The metsulfuron methyl 20% WG @ 20 g ha⁻¹ and clodinafop 15% WP @ 400 g ha⁻¹ were sprayed at 52 and 53 DAS, respectively in all the treatments. The DSR plots were sprayed with pre-emergence herbicide (pendimethline 30EC @ 2.5 l ha⁻¹)

immediately after sowing. The crop was sprayed with post-emergence herbicide (bispribac sodium 10% SC @ 250 g ha⁻¹) at 23 DAS. The weeds surviving these treatments were removed manually as and when these appeared. In puddle plots of DSR and MTR, the weeds were controlled by applying post-emergence herbicide butachlor @ 150 g ha⁻¹ at 15 DAT. The crop was protected against insect-pests by spraying chloropyriphos @ of 2.5 l ha⁻¹ at 57 DAS in all the treatments. However, monocrotophos @ 50.4 g ha⁻¹ and propiconazole @ 62.5 g ha⁻¹ was used to control insects and diseases in rice season.

2.6 Observations

Periodic tiller density (number m⁻²) was measured in 0.5-m row length at four fixed places in each plot. The crop biomass accumulation was measured every fortnight in 1-m row length at two places in each plot, the sub-samples of which were dried at 60°C for 72 h and weighed. Periodic leaf area index (LAI) was measured using a Delta-T Sunscan probe. Measurements were made across five rows, with the probe parallel to the rows every time at a fixed location in each plot.

For recording the grain yield, an area of 10 m² was harvested from the centre of each plot, thrashed manually for rice and by mechanical thrasher for wheat. The moisture content of the grains was recorded using moisture meter and the crop yield was determined at 12% moisture for wheat and 14% for rice. The straw yield of both the crops was adjusted to zero percent moisture content. Harvest index was calculated as the ratio of grain yield and total biological yield (grain + straw). The average grain weight was determined as average weight of 1000 fresh grains and expressed at 14 and 12% moisture contents for rice and wheat, respectively. The grains per panicle in wheat were recorded in 10 panicles selected randomly for each plot. The floret fertility percentage in rice was measured in 10 panicles selected randomly from each plot at harvest. The filled and unfilled florets per panicle were counted and fertility percentage calculated as the ratio of filled and total florets from each panicle. The weeds were removed and weighed after sun drying for 3-4 days to record weed biomass.

The irrigation water amounts were measured using digital flow meter (AVFM 5.0) fixed at the inlet point of each plot. The irrigation water productivity (WP_I) was calculated as the ratio of the recorded grain yield to the total amount of irrigation water, whereas total input water productivity (WP_{I+R}) was calculated as the ratio of grain yield to the total input (irrigation + rainwater).

2.7 Weather data

Daily maximum and minimum temperature and pan evaporation were measured at the PAU meteorological station, about 1.5 km from the experimental site. Rainfall was measured using an automatic rain gauge installed at the experimental site.

2.7 Statistical analyses

The data so obtained was analyzed by analysis of variance (ANOVA) using GenStat V.10.3 software. The treatment means were compared by least significant difference (LSD) at 5% level of probability.

3. Results

3.1 Weather

The maximum temperature during the months of March-May was slightly higher in 2012-13 than in 2013-14 and the long-term average maximum temperature. It reversed during June-October being lower in 2012-13 than in 2013-14 and the long term average. However, the minimum temperature was almost similar in the two years, being slightly higher than the long term average during June-July and October (Fig. 1a). The pan evaporation was similar during November-April in the two years of study. However, it was higher during June-September in 2013-14 than in 2012-13 and the long term average (Fig. 1b). The total amount of rainfall was higher (891.6 mm) in 2012-13 than in 2013-14 (582.3 mm) (Fig. 1c), but the rains were better distributed during 2013-14 (42 rainy days) than during 2012-13 (31 rainy days). The month of June recorded abnormally higher rainfall (296.4 mm) during 2012-13 compared to 30.3 mm during 2013-14 (Fig. 1d).

3.2 Crop performance

3.2.1 Wheat

3.2.1.1 Growth parameters

The crop stand and growth in all the plots was generally good in both the years as indicated by the coefficient of variation of biomass production within the treatments which ranged from 2.1 to 27.4% during 2012-13 and 2.5 to 31% during 2013-14. The wheat biomass in ZTW plots during 2012-13 was slightly lower than that in CTW plots till 110 DAS but later on the biomass was higher in ZTW plots than in the CTW plots (Fig. 2a). It was 11% higher at 131 DAS and the difference decreased to 6% at 156 DAS. During 2013-14, the wheat biomass was similar in ZTW and CTW plots throughout the crop season (Fig. 3a). The residual effect of

the rice establishment method on wheat biomass was not observed at all the observed growth (Fig. 3b).

The tiller density of wheat was initially higher in CTW plots than in ZTW plots during both the years (Fig. 2b, 3d), but it was similar during the later growth stages with respect to tillage in wheat and rice and rice establishment method (Fig. 3e-f). The leaf area index (LAI) of wheat was higher in CTW than in ZTW plots at all the crop stages during both the years (Fig. 2c, 3g). It was statistically similar with respect to establishment method (Fig. 3h) and tillage in rice (Fig. 3i).

3.2.1.2 Yield parameters

The yield attributes viz. grains per panicle, average grain weight and harvest index of wheat were not affected significantly by tillage in wheat, establishment method and tillage in rice (Table 4, 5 & 6).

3.2.1.3 Grain yield

In general, the grain yield of wheat was higher in 2013-14 than in 2012-13. This could be due to the higher maximum and minimum temperatures during February-April in 2012-13 than in 2013-14. The grain yield of wheat was similar in CTW and ZTW plots during both the years. The establishment method and tillage in rice did not affect the wheat grain yield significantly during 2013-14 (Table 7), though it was slightly higher in CTW than in ZTW plots. The difference in wheat yield decreased from 9.7% in 2012-13 to 7.0% in 2013-14. The wheat yield was not affected by the tillage and establishment method of rice during 2013-14 (Table 7).

3.2.2 Rice

3.2.2.1 Growth parameters

The biomass of rice was higher in CTW than in ZTW plots during 2013 (Fig. 4a) but it was similar in the two treatments during 2014 (Fig. 5a). The establishment method of rice significantly affected the crop biomass, being higher in DSR than in the MTR plots during both the years of study (Fig. 4b, 5b), the differences being higher during 2014. The average crop biomass was significantly lower in zero-till rice than in puddle CT plots (Fig. 4c, 5c), irrespective of the establishment method during both the years.

The tiller density was not affected significantly by tillage in wheat during both the years (Fig. 4d, 5d). It was initially higher in DSR plots but at later stages (130 DAS onwards), the MTR plots recorded higher tiller density than DSR plots during 2013 (Fig. 4e). In 2014, the tiller density though being higher initially in

DSR plots was statistically similar to that in MTR plots during later stages (Fig. 5 e). The effective tillers were similar with respect to tillage in rice during both the years (Fig 4f, 5f).

The LAI was slightly higher in CTW than in ZTW plots throughout the growing season during 2013 and 2014 (Fig. 4g, 5g). It was significantly higher at 117 DAS in former than in later plots during 2013 (Fig. 4g). The establishment method significantly affected the LAI throughout the crop growth during both the years (Fig. 4h, 5h), being higher by 50% at all the crop growth stages in DSR plots than in MTR plots in 2013 and the difference increased to 115% during 2014. The tillage in rice did not affect LAI in 2013 (Fig. 4i). However, it was significantly higher in puddle than in CT and ZT plots at 106 DAS during 2014 (Fig. 5i).

3.2.2.2 Yield parameters

The floret fertility percentage was not affected by tillage in wheat during both the years of study (Table 4). The DSR plots on an average had 10.1 and 15.9% higher floret fertility during 2013 and 2014 respectively, than in MTR plots, the difference being significant at 5% level of significance. The fertility percentage was highest in puddle followed by CT plots and lowest in ZT plots, the differences being significant in 2013. In 2014, the puddle and CT plots had similar fertility percentage which was significantly higher than that in ZT plots.

The average grain weight was significantly higher in CTW than in ZTW plots during 2014, while in 2013 it was similar in the two treatments (Table 5). The DSR and MTR plots had similar average grain weight during both the years. The tillage in rice significantly affected the average grain weight of rice, being highest in puddle, followed by CT plots and lowest in ZT plots both under DSR and MTR. The average grain weight in 2014 was higher in puddle and CT plots of DSR as compared to MTR plots, whereas in ZT plots, the establishment method did not affect the average grain weight. The HI was not affected by tillage in wheat during 2013 but in 2014 it was significantly higher in CTW than in ZTW plots (Table 6). It was highest in puddle plots, followed by CT and lowest in ZT plots under both the methods of establishment. The HI was significantly higher in ZT plots of MTR than in DSR.

3.2.2.3 Grain yield

The grain yield of rice was higher in CTW than in ZTW plots during both the years, the differences being statistically significant during 2014. The grain yield of DSR was similar to that of MTR during 2013 but the difference became statistically

significant during 2014, being higher in DSR. The tillage in rice significantly affected the grain yield in the order puddle > dry tilled > zero till plots during both the years. The average grain yield decreased by 17.2% in 2013 and 27.7% in 2014 in CT plots from that in puddle plots. It further decreased by 24.4 and 28.4% in ZT plots, respectively (Table 7). The grain yield in 2014 was significantly higher in puddle and ZT plots of DSR than the MTR. The trend was similar in 2013 but the differences were statistically non-significant (Table 7).

3.3 Irrigation water productivity

3.3.1 Wheat

The irrigation water productivity (WP_I) of wheat was significantly lower in ZTW (1.81 g kg^{-1}) than in the CTW plots (2.16 g kg^{-1}) during 2012-13. However, it was similar in the two treatments during 2013-14 (Table 9). The establishment method and tillage in rice had no significant effect on WP_I during 2013-14. The average WP_I of wheat was similar in puddled and CT plots of rice but was significantly higher in ZT plots of rice. The decrease in WP_I of wheat in ZTW plots from that in CTW plots was more pronounced in puddle and CT than in ZT plots of rice.

3.3.2 Rice

The average WP_I was higher in CTW than in ZTW plots during both the years, the differences being significant during 2014. The WP_I of MTR was 31.1% higher in CTW than in ZTW plots compared to 9.5% during 2013. The mean WP_I was 15% higher in CTW than in ZTW plots during 2014. The average WP_I of MTR was significantly higher than that of DSR during both the years. The WP_I of rice in puddle, CT and ZT plots was similar in 2013 but the differences became significant during 2014. It was sufficiently higher in puddle (0.56 g kg^{-1}) plots than in CT (0.29 g kg^{-1}) and ZT (0.25 g kg^{-1}) plots. The WP_I was higher by 48.9% in puddle plots, 32% in CT and 38.1% in ZT plots of MTR than in DSR in 2014.

3.4 Cropping system productivity

3.4.1 Land productivity

The land productivity of wheat-rice cropping system was significantly affected by tillage in wheat during both the years. It was 15.8 and 11.3% higher in CTW than in ZTW plots during 2012-13 and 2013-14, respectively (Table 10). The land productivity of wheat-rice was similar in DSR and MTR plots during both the

years. The tillage in rice significantly affected total land productivity in both the years, being highest in puddle followed by CT and lowest in ZT plots.

3.4.2 Irrigation water productivity

The WP_I of wheat-rice cropping system was significantly higher (16-19.5%) in CTW than in ZTW plots during 2012-14 (Table 10). The establishment method of rice significantly affected the WP_I of the cropping system, being higher in MTR (0.81-0.88 g kg⁻¹) than in DSR (0.60-0.77 g kg⁻¹) plots. The tillage in rice significantly affected WP_I of the cropping system during both the years. The WP_I of wheat-rice cropping system, though similar in CT (0.76 g kg⁻¹) and ZT (0.71 g kg⁻¹) plots of rice during 2012 -13, was 11.2% lower in ZT plots during 2013-14. The decrease in system WP_I in 2012-13 due to zero tillage in wheat was highest (18.4%) in puddle plots, followed by 15.7% in CT and lowest (9.8%) in ZT plots of rice. Similar trend was observed in 2013-14.

4. Discussion

4.1 Weather and crop performance

The wheat grain yield, in general, was higher during 2013-14 than during 2012-13. This could be mainly because of maximum and minimum temperatures (Fig. 1a) remaining higher during the months of February-April in 2012-13 than in 2013-14. These were even higher than the long term average (Fig. 1a). Higher temperature during the month of February results in greater respiration leading to shrinkage of grains and hence lowers the average grain weight, which was 34.4 mg during 2012-13 compared to 36.4 mg during 2013-14. Moreover, higher rainfall during February-April in 2012-13 than during 2013-14 (Fig. 1c) could have resulted in washing down of pollens leading to lesser number of grains panicle⁻¹ (Table 4). These were 51 in 2012-13 compared to 58.4 during 2013-14. The rice yields were almost similar in 2012-13 and 2013-14 due to similar temperature conditions during the months of July-October.

4.2 Crop and cropping system productivity

4.2.1 Wheat

Similar grain yield of wheat in CTW and ZTW plots despite of higher weed biomass in ZTW indicates that zero tillage can result in higher wheat productivity if the weeds are managed efficiently through effective herbicide use. In fact, zero tillage results in accumulation of weed seeds on or near to the soil surface after sowing which may encourage higher germination percentage of these seeds due to

better availability of sunlight, moisture and nutrients (Singh et al., 2015a). The zero tillage gradually increases the mechanical impediment of the surface soil, limiting the distribution of roots in plough layer (Mossaddeghi et al., 2009). The root mass density in DT plots was 37.3% higher than in the ZT plots in upper 0-15cm soil layer (data not presented).

The higher biomass during later crop growth stage (Fig. 2a) in 2012-13 was not reflected in wheat grain yield, though in 2013-14 it was behaved similar to wheat grain yield with respect to tillage in wheat. The wheat growth, yield attributes and grain yield were not affected by tillage and establishment method of rice. The contradictory reports of wheat performance under zero tillage in the literature (Singh et al., 2011; Guan et al., 2015) are mainly due to the site-specific conditions related to weed intensity and soil edaphic environment affecting root proliferation and water transmission characteristics.

4.2.2 Rice

The zero tillage in wheat affected the rice grain yield, which decreased significantly during second year of study. It could be due mainly due to significantly due higher weed biomass in ZTW plots during both the years. Interestingly, the weed biomass in ZTW plots increased by 16.7% in 2014 from that in 2013. The DSR performed better than MTR with significant difference in 2014. The grain yield of DSR was better than MTR under all the tillage treatments in rice viz. puddle, CT and ZT. It could be due to the transplanting shock to MTR (Kamboj et al., 2013) in comparison to DSR. The wider row spacing of MTR seedlings though resulted in higher tiller density (Fig. 4e, 5e), but lower fertility percentage, average grain weight and HI lowered the MTR yields. The significantly higher rice grain yield in puddle plots was mainly due to higher fertility percentage, HI and average grain weight as compared to CT and ZT plots. These effects were further compounded by higher weed biomass in ZT and CT plots as also observed by Singh et al. (2015a) and Singh et al. (2015b). The severe iron deficiency in ZT plots despite of FeSO_4 sprays might have lowered the rice grain yields in ZT plots as also observed by Yadvinder-Singh et al. (2009) and Jat et al. (2009).

4.2.3. Wheat-rice cropping system

The significant reduction in cropping system productivity due to zero tillage in wheat was due to the yield loss both in wheat and rice (Table 10). Jat et al. (2014) observed that zero tillage without mulch yielded poorly as compared to dry till plots.

The total land productivity was similar in DSR and MTR plots. The land productivity was highest (11.5 Mg ha⁻¹) in CTW-DSR-P scenario during 2012-13 and 12.6 Mg ha⁻¹ during 2013-14, followed by CTW-MTR-P, CTW-DST-CT and was lowest in ZTW-MTR-ZT. The establishment method of rice does not seem to affect the productivity of wheat-rice system. Tillage in wheat on the other hand significantly affected the productivity of the cropping system. The tillage in rice played a major role in affecting the productivity of the system increasing it in the order puddle > CT > ZT. Puddling might have affected the system productivity through its beneficial effects viz. destroying weed seed, reducing leaching losses (Kumar and Ladha, 2011) and improving soil water retention (Kukul et al., 2003b; Kukul and Sidhu, 2004).

4.3 Irrigation water productivity

4.3.1 Wheat

The significantly higher (2.16 g kg⁻¹) water productivity (WP_I) of wheat during 2012-13 in CTW plots than in the ZTW plots (1.81 g kg⁻¹) despite of the similar irrigation water consumption is mainly due to higher grain yield of wheat in the former plots (Table 9). However, in 2013-14, WP_I was statistically similar in two tillage methods due to saving of one irrigation in the ZTW plots. In fact, the poor crop growth including the root biomass (data not presented) in ZT plots led to lower uptake of water from the root zone for transpiration compared to that in CTW plots. Since the plots were irrigated on the basis of soil matric potential, the lower soil water depletion in ZT plots might have resulted in saving of one irrigation. The WP_I of wheat was not significantly affected by the establishment method. Tillage in rice affected the WP_I of wheat 2013-14, being statistically higher in ZT than in CT plots. It was similar in puddle and CT plots. This could again be due to the similar reason as explained above.

4.3.2 Rice

The higher irrigation water productivity of rice in CTW plots during 2014 was mainly because of higher grain yields with similar irrigation water consumption as compared to that in ZTW plots (Table 9). The significantly higher WP_I of mechanically transplanted rice compared to the direct seeded rice during both the years was mainly due to 23.5-63.5% higher irrigation water consumed in the DSR plots. In fact, the DSR with longer crop duration in the field experiences higher evapo-transpiration losses as compared to the MTR plots, thereby consuming higher

irrigation water. The highest WP_I in puddle plots was due to the lowest amount of the irrigation water consumption in these plots during both the years, followed by that in ZT and highest in CT plots. The lowest irrigation water consumption in puddle plots is due to three time higher infiltration rate of un-puddled as compared to puddle soil (Kukal et al., 2009; Singh et al., 2011; Kukal et al., 2014). This increases the amount of irrigation water per irrigation in un-puddled plots. Moreover, the higher irrigation water consumption in CT compared to ZT plots was mainly due to the lower residence time of moving water in ZT plots particularly in the absence of any straw retention at the soil surface.

In general, the WP_I of rice was higher during 2013 than in 2014. It could be due to higher (39%) and well distributed rainfall (23 rainy days) during 2013. The higher decrease in irrigation water productivity from puddle to CT plots in MTR (50.7%) compared to DSR (44.4%) plots may be due to significantly lower grain yield of former than in later.

4.3.3. *Wheat-rice cropping system*

The zero tillage in wheat significantly decreased the average WP_I of the cropping system during both the years which was due to the lower grain yield of both the crops in zero till plots (Table 10). However, the higher WP_I of MTR plots compared to the DSR was due to significantly lower amount of irrigation water consumed in the former plots because of shorter duration of MTR crop in the field than that of DSR crop. The puddling resulted in highest WP_I (0.9-1.0 g kg⁻¹) among all the rice tillage treatments due to higher grain yield as well as lower irrigation inputs as explained earlier. The WP_I of the cropping system was, however similar in CT and ZT plots during 2012-13 but during 2013-14, it was significantly higher in ZT plots. It is due to lower irrigation water amount consumed in both wheat and rice crops grown in ZT plots. The WP_I of both DSR and MTR was significantly higher in puddle plots than CT and ZT plots because of consumption of lower irrigation water amounts and reported higher grain yields.

5. Conclusion

The results lead us to the conclusion that the conventional tillage in wheat and rice resulted in higher land and irrigation water productivity in wheat-rice cropping system. The zero tillage though did not affect the land and irrigation water productivity of wheat, but it decreased these for the cropping system as a whole. The establishment method of rice had no impact on the land productivity of the cropping

system, but the WP_I of the system was higher in MTR than in DSR. The land productivity of the wheat-rice cropping system was highest in CTW-DSR-P scenario and lowest in ZTW-MT-ZT scenario while irrigation water productivity of the system was highest in CTW-MT-P scenario and lowest in ZTW-DSR-ZT scenario.

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Table 1

Basic physico-chemical properties of the studied site

Depth (cm)	Sand (%)	Clay (%)	pH (2:1)	EC (2:1)	O.C (%)	Available nutrients (kg ha ⁻¹)			Db (Mg m ⁻³)	Moisture content (%) w/w)	
						N	P	K		At 0.3 bar	At 15 bars
0-15	64.7	11.3	7.26	0.25	0.45	341.2	15.2	250.8	1.66	11.3	7.7
15-30	65.9	11.3	7.23	0.31	0.44	332.8	14.2	218.6	1.74	10.4	6.2
30-60	66.8	12.6	7.31	0.32	0.35	--	--	--	1.59	12.1	6.4
60-90	67.6	12.7	7.18	0.26	0.37	--	--	--	1.63	11.3	6.7
90-120	68.2	12.3	7.01	0.34	0.34	--	--	--	1.57	12.1	7.3
120-150	68.8	11.9	7.08	0.33	0.32	--	--	--	1.61	12.5	6.6

Table 2

Quality of irrigation water used at the experimental site

Replications	Ca ²⁺ +Mg ²⁺ (meq/l)	Cl ⁻ (meq/l)	Residual NaHCO ³	EC (dsm ⁻¹)	CO ₃ ²⁻ (meq/l)	HCO ³⁻ (meq/l)
R1	3.5	0.7	0.0	0.47	0.0	3.5
R2	3.7	0.8	0.0	0.49	0.0	4.0
R3	3.5	0.9	0.0	0.53	0.0	3.7

Abbreviations and details of tillage, crop establishment And residue management under the experiment

Sr. No	Treatments		Tillage		Crop establishment		Residue management	
	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice
1	CTW	DSR-P	Conventional tillage-Three passes of disc plough followed by two passes of cultivator followed by one planking.	Puddling- Four passes of power tiller in standing water. Puddling done twice one a day before and one on sowing day	Sowing of seeds done with pre-calibrated seed drill at a row to row 20 cm spacing at 112.5 kg ha ⁻¹ .	DSR-P-Drum seeder with 20 cm row to row spacing used to sow pre-germinated seeds on puddle plots.	Incorporated	All removed
2	CTW	DSR-CT				DSR-CT-Seed drill used to sow seeds at 20 cm spacing in conventionally tilled plots.	-do-	-do-
3	CTW	DSR-ZT				DSR-ZT-Same as above in undisturbed plots.	-do-	-do-
4	CTW	MTR-P				MT-P-Mechanical transplanter used to establish mat type nursery at 30 cm row to row spacing with 17 cm plant to plantspacing in pre-puddled plots	-do-	-do-
5	CTW	MTR-CT				MT-CT- Same as above in conventionally tilled plots.	-do-	-do-
6	CTW	MTR-ZT				MT-ZT-Same as above in undisturbed plots.	-do-	-do-
7	ZTW	DSR-P	Zero tillage-No tillage operation performed in zero tillage plots.	Zero tillage-Rice seeds directly drilled in standing wheat stubbles.			4.4 t ha ⁻¹ retained	-do-
8	ZTW	DSR-CT					-do-	-do-
9	ZTW	DSR-ZT					-do-	-do-
10	ZTW	MTR-P					-do-	-do-
11	ZTW	MTR-CT					-do-	-do-
12	ZTW	MTR-ZT					-do-	-do-

Table 4Interactive effect of tillage and establishment methods on grain panicle⁻¹ and floret fertility % of wheat and rice during 2012-2014

Establishment methods	Tillage (Rice)	Wheat (2012-13)		Rice (2013)			Wheat (2013-14)			Rice (2014)		
		Grain panicle ⁻¹		Fertility percentage			Grain panicle ⁻¹			Fertility percentage		
		CTW	ZTW	CTW	ZTW	Mean	CTW	ZTW	Mean	CTW	ZTW	Mean
DSR	P	--	--	88.3	86.9	87.6	59.8	57.8	58.8	86.1	85.8	86.0
	CT	--	--	84.8	83.6	84.2	59.2	63.6	61.4	82.2	83.4	82.8
	ZT	--	--	81.8	79.0	80.4	52.8	60.8	56.8	77.7	75.5	76.6
Mean			--	85.0	83.2	84.1	57.3	60.7	59.0	82.0	81.6	81.8
MTR	P	--	--	80.4	80.4	80.4	61.8	59.4	60.6	68.2	74.3	71.3
	CT	--	--	79.3	77.1	78.2	58.3	53.3	55.8	70.6	68.1	69.4
	ZT	--	--	71.1	69.9	70.5	53.2	60.3	56.8	71.8	70.7	71.3
Mean		51.1	50.9	76.9	75.8	76.4	57.8	57.7	57.7	70.2	71.0	70.6
<i>Treatment means</i>												
CTW		51.1			80.9			57.5			76.1	
ZTW		50.9			79.5			59.2			76.3	
DSR					84.1			59.0			81.8	
MTR					76.4			57.7			70.6	
P					84.0			59.7			78.6	
CT					81.2			58.6			76.1	
ZT					75.5			56.8			73.9	
LSD _{0.05}												
Tillage (Wheat)		NS			NS			NS			NS	
Est Methods (Rice)					1.24			NS			2.6	
Tillage (Rice)					0.84			NS			2.8	
TW×EM(R)					NS			NS			NS	
EM(R)×T(R)					1.18			NS			3.9	
T(W) ×T(R)					NS			NS			NS	

Table 5

Interactive effect of tillage and establishment methods in wheat and rice on average grain weight (mg) of wheat and rice during 2012-2014

Establishment methods	Tillage (Rice)	Wheat (2012-13)		Rice (2013)			Wheat (2013-14)			Rice (2014)		
		CTW	ZTW	CTW	ZTW	Mean	CTW	ZTW	Mean	CTW	ZTW	Mean
DSR	P	--	--	20.2	20.2	20.2	37.2	36.9	37.1	23.6	21.3	22.5
	CT	--	--	18.4	19.3	18.9	37.7	35.6	36.7	20.1	19.4	19.8
	ZT	--	--	17.9	17.2	17.6	38.0	35.2	36.6	19.6	17.8	18.7
Mean		--	--	18.8	18.9	18.9	37.6	35.9	36.8	21.1	19.5	20.3
MTR	P	--	--	22.7	19.0	20.9	38.7	34.1	36.4	23.4	21.7	22.6
	CT	--	--	18.5	17.5	18.0	35.9	37.0	36.4	20.4	19.3	19.9
	ZT	--	--	17.1	15.7	16.4	37.2	33.4	35.3	18.5	18.8	18.7
Mean		34.6	34.2	19.4	17.4	18.4	37.3	34.8	36.1	20.8	19.9	20.3
<i>Treatment means</i>												
CTW		34.6			19.1			37.5			21.0	
ZTW		34.2			18.1			35.4			19.7	
DSR					18.8			36.8			20.4	
MTR					18.4			36.1			20.3	
P					20.5			36.7			22.5	
CT					18.4			36.6			20.0	
ZT					17.0			36.0			18.7	
LSD _{0.05}												
Tillage (Wheat)		NS			NS			NS			1.11	
Est Methods (Rice)					NS			NS			NS	
Tillage (Rice)					1.57			NS			0.41	
TW×EM(R)					NS			NS			NS	
EM(R)×T(R)					NS			NS			NS	
T(W) ×T(R)					NS			NS			0.58	

Table 6

Interactive effect of tillage and establishment methods on harvest index of wheat and rice during 2012-2014

Establishment methods	Tillage (Rice)	Wheat (2012-13)		Rice (2013)			Wheat (2013-14)			Rice (2014)		
		CTW	ZTW	CTW	ZTW	Mean	CTW	ZTW	Mean	CTW	ZTW	Mean
DSR	P	--	--	0.26	0.23	0.25	0.43	0.41	0.42	0.28	0.25	0.27
	CT	--	--	0.23	0.23	0.23	0.40	0.42	0.41	0.24	0.25	0.25
	ZT	--	--	0.19	0.19	0.19	0.38	0.40	0.39	0.24	0.20	0.22
Mean		--	--	0.23	0.22	0.22	0.40	0.42	0.41	0.25	0.23	0.24
MTR	P	--	--	0.21	0.16	0.19	0.40	0.40	0.40	0.30	0.28	0.29
	CT	--	--	0.18	0.15	0.17	0.38	0.40	0.39	0.28	0.24	0.26
	ZT	--	--	0.17	0.16	0.17	0.39	0.41	0.40	0.20	0.18	0.19
Mean		0.447	0.448	0.19	0.16	0.18	0.39	0.40	0.40	0.26	0.23	0.25
Treatment means												
CTW		0.447		0.21		0.40		0.26				
ZTW		0.448		0.19		0.41		0.23				
DSR				0.23		0.41		0.24				
MTR				0.18		0.40		0.25				
P				0.22		0.41		0.28				
CT				0.20		0.40		0.25				
ZT				0.18		0.40		0.21				
LSD _{0.05}												
Tillage (Wheat)		NS		NS		NS		0.02				
Est Methods (Rice)				NS		NS		NS				
Tillage (Rice)				0.02		NS		0.02				
TW×EM(R)				NS		NS		NS				
EM(R)×T(R)				NS		NS		0.03				
T(W) ×T(R)				NS		NS		NS				

Table 7Interactive effect of tillage and establishment method on grain yield (Mg ha⁻¹) of wheat and rice during 2012-2014

Establishment methods	Tillage (Rice)	Wheat (2012-13)		Rice (2013)		Mean	Wheat (2013-14)			Rice (2014)		
		CTW	ZTW	CTW	ZTW		CTW	ZTW	Mean	CTW	ZTW	Mean
DSR	P	--	--	6.20	4.50	5.35	6.60	5.33	5.97	5.97	5.20	5.59
	CT	--	--	4.60	4.20	4.40	6.10	5.73	5.92	4.10	3.70	3.90
	ZT	--	--	2.90	2.90	2.90	5.23	5.40	5.32	3.70	2.97	3.34
Mean		--	--	4.56	3.86	4.21	5.97	5.49	5.73	4.59	3.96	4.28
MTR	P	--	--	5.03	4.13	4.55	5.50	5.07	5.29	5.47	4.61	5.04
	CT	--	--	4.27	3.33	3.80	5.30	5.10	5.14	3.99	3.57	3.79
	ZT	--	--	3.80	2.53	3.15	5.63	5.27	5.45	2.45	1.87	2.17
Mean		5.27	4.76	4.36	3.30	3.83	5.47	5.15	5.29	3.98	3.35	3.67
<i>Treatment means</i>												
CTW		5.27		4.46				5.72		4.29		
ZTW		4.76		3.63				5.32		3.65		
DSR				4.26				5.73		4.28		
MTR				3.83				5.29		3.67		
P				4.95				5.63		5.31		
CT				4.10				5.53		3.84		
ZT				3.10				5.38		2.75		
LSD _{0.05}												
T (W)		NS		NS				NS		0.15		
EM(R)				NS				NS		0.14		
T(R)				0.46				NS		0.20		
TW×EM (R)				NS				NS		NS		
EM(R)×T (R)				NS				NS		0.20		
T(W) ×T (R)				NS				NS		NS		

Table 8Interactive effect of tillage and establishment methods on weed biomass (t ha⁻¹) in wheat and rice during 2012-2014

Establishment methods	Tillage (Rice)	Wheat (2012-13)		Rice (2013)			Wheat (2013-14)			Rice (2014)		
		CTW	ZTW	CTW	ZTW	Mean	CTW	ZTW	Mean	CTW	ZTW	Mean
DSR	P	--	--	0.58	0.65	0.62	0.10	0.19	0.45	0.72	0.76	0.74
	CT	--	--	0.75	1.02	0.89	0.25	0.48	0.36	0.86	1.11	0.98
	ZT	--	--	0.81	1.20	1.00	0.05	4.04	2.04	1.11	1.46	1.29
Mean		--	--	0.71	0.96	0.84	0.13	1.77	0.95	0.89	1.11	1.00
MTR	P	--	--	0.72	0.74	0.73	0.06	0.90	0.48	0.74	0.83	0.79
	CT	--	--	0.89	0.88	0.89	0.21	1.38	0.79	0.96	1.02	0.99
	ZT	--	--	0.92	1.27	1.09	0.09	2.58	1.34	1.15	1.54	1.35
Mean		0.27	0.39	0.84	0.96	0.90	0.12	1.62	0.87	0.95	1.13	1.04
<i>Treatment means</i>												
CTW		0.27			0.78			0.13			0.92	
ZTW		0.39			0.96			1.70			1.12	
DSR					0.84			0.95			1.00	
MTR					0.90			0.87			1.04	
P					0.68			0.47			0.76	
CT					0.89			0.58			0.99	
ZT					1.05			1.69			1.32	
LSD _{0.05}												
T (W)		0.11			0.13			0.69			0.13	
EM(R)					0.05			NS			NS	
T(R)					0.10			0.29			0.09	
TW×EM (R)					NS			NS			NS	
EM(R)×T (R)					NS			0.41			NS	
T(W) ×T (R)					0.14			0.41			0.14	

Table 9Interactive effect of tillage and establishment methods on irrigation water productivity (g kg⁻¹) of wheat and rice during 2012-2014

Est. methods	Tillage (Rice)	Wheat (2012-13)		Rice (2013)			Wheat (2013-14)			Rice (2014)		
		CTW	ZTW	CTW	ZTW	Mean	CTW	ZTW	Mean	CTW	ZTW	Mean
DSR	P	--	--	0.65	0.55	0.60	2.70	2.20	2.45	0.47	0.42	0.45
	CT	--	--	0.43	0.42	0.43	2.53	2.27	2.40	0.27	0.22	0.25
	ZT	--	--	0.31	0.29	0.30	2.03	3.00	2.52	0.23	0.19	0.21
Mean		--	--	0.46	0.42	0.45	2.42	2.49	2.46	0.32	0.28	0.30
MTR	P	--	--	0.81	0.66	0.74	2.30	2.07	2.19	0.70	0.63	0.67
	CT	--	--	0.47	0.36	0.42	2.10	2.10	2.10	0.34	0.31	0.33
	ZT	--	--	0.48	0.32	0.40	2.30	2.83	2.57	0.34	0.23	0.29
Mean		2.16	1.81	0.59	0.45	0.52	2.23	2.33	2.29	0.46	0.39	0.43
<i>Treatment means</i>												
CTW		2.16			0.53			2.33			0.39	
ZTW		1.81			0.44			2.41			0.34	
DSR					0.45			2.46			0.30	
MTR					0.52			2.29			0.43	
P					0.67			2.32			0.56	
CT					0.43			2.25			0.29	
ZT					0.36			2.54			0.25	
LSD _{0.05}												
Tillage (Wheat)		0.25			NS			NS			0.02	
Est Methods (Rice)					0.06			NS			0.01	
Tillage (Rice)					NS			0.22			0.02	
TW×EM(R)					0.06			NS			NS	
EM(R)×T(R)					NS			NS			0.03	
T(W) ×T(R)					NS			0.32			NS	

Table 10

Interactive effect of tillage and establishment method on land (Mg ha^{-1}) and irrigation water productivity (g kg^{-1}) of rice-wheat system during 2012-14

Establishment methods	Tillage (Rice)	2012-13						2013-14					
		Land productivity (Mg ha^{-1})			Irrigation water productivity (g kg^{-1})			Land productivity (Mg ha^{-1})			Irrigation water productivity (g kg^{-1})		
		CTW	ZTW	Mean	CTW	ZTW	Mean	CTW	ZTW	Mean	CTW	ZTW	Mean
DSR	P	11.5	9.26	10.4	0.96	0.86	0.91	12.6	10.5	11.6	0.83	0.71	0.77
	CT	9.87	8.96	9.42	0.79	0.72	0.76	10.2	9.43	9.82	0.58	0.50	0.54
	ZT	8.17	7.66	7.92	0.65	0.60	0.63	8.93	8.37	8.65	0.48	0.47	0.48
Mean		9.84	8.71	9.25	0.80	0.73	0.77	10.6	9.44	10.0	0.63	0.56	0.60
MTR	P	10.3	8.89	9.60	1.19	1.01	1.10	11.0	9.67	10.3	1.10	1.00	1.05
	CT	9.54	8.09	8.82	0.83	0.68	0.76	9.17	8.67	8.99	0.63	0.61	0.62
	ZT	9.07	7.29	8.18	0.87	0.68	0.78	8.10	7.14	7.62	0.84	0.72	0.78
Mean		9.64	8.10	8.87	0.96	0.79	0.88	9.41	8.49	8.98	1.29	0.78	0.82
<i>Treatment means</i>													
CTW			9.74			0.88			9.99			0.74	
ZTW			8.41			0.76			8.97			0.67	
DSR			9.25			0.77			10.01			0.60	
MTR			8.87			0.88			8.98			0.81	
P			10.0			1.00			10.94			0.90	
CT			9.12			0.76			9.41			0.58	
ZT			8.05			0.71			8.14			0.63	
LSD _{0.05}													
Tillage (Wheat)			0.88			0.04			0.73			0.03	
Est Methods (Rice)			NS			0.04			NS			0.07	
Tillage (Rice)			0.46			0.05			0.55			0.03	
TW×EM(R)			NS			NS			NS			NS	
EM(R)×T(R)			NS			0.07			NS			0.05	
T(W) ×T(R)			NS			NS			NS			NS	

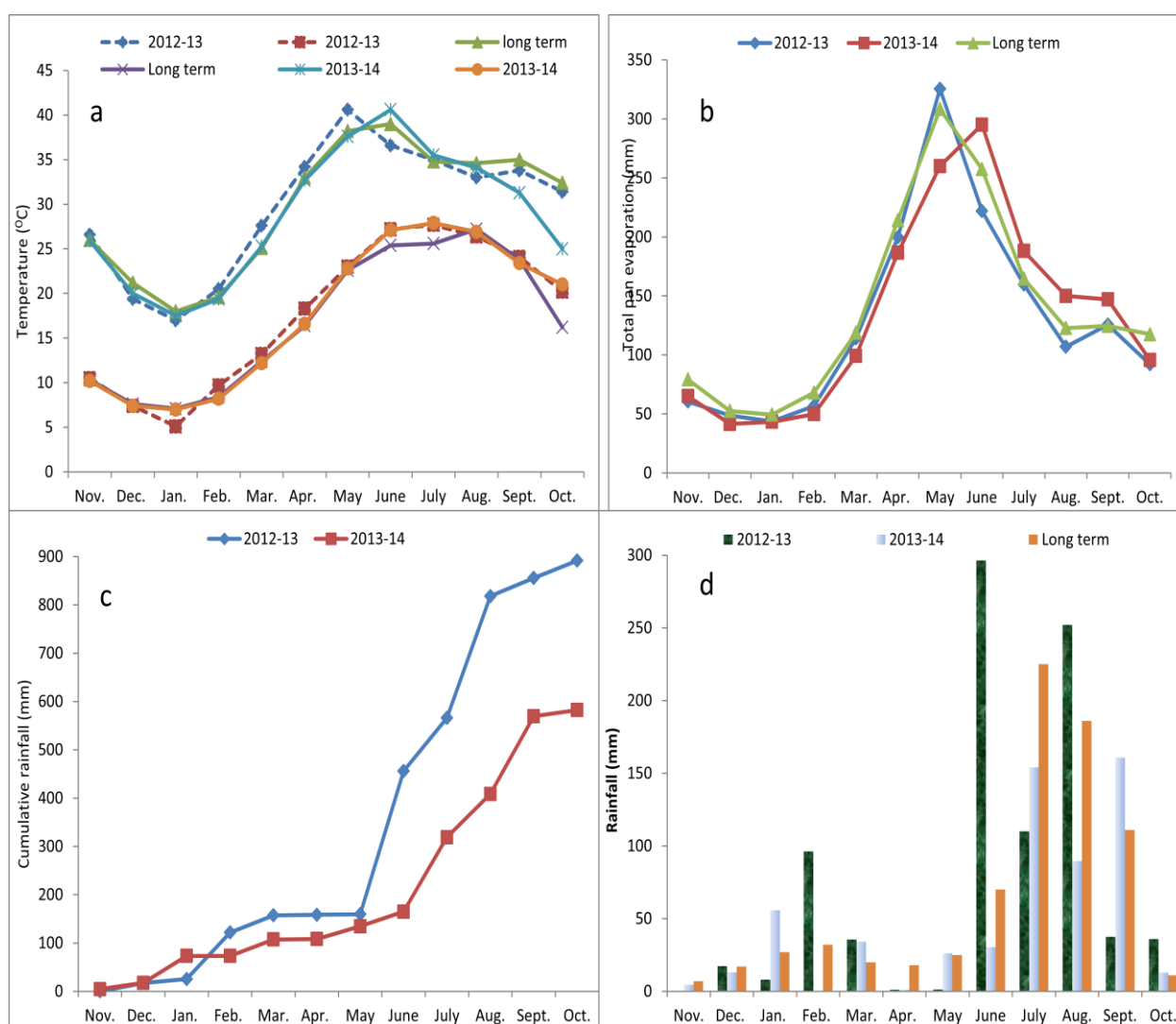


Fig.1 Mean monthly maximum and minimum temperatures (a), pan evaporation (b), cumulative rainfall (c) and monthly rainfall distribution (d) during the study period (2012-14).

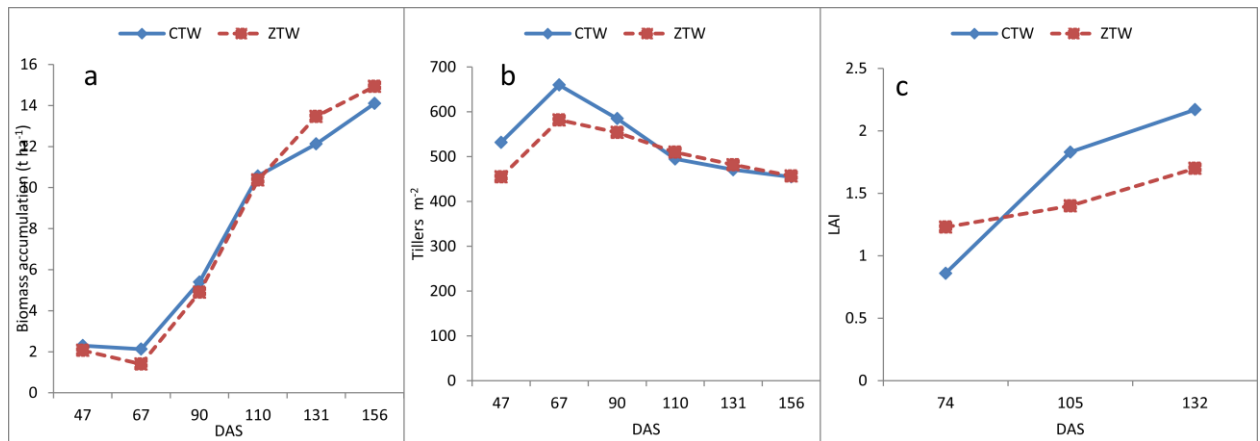


Fig. 2 Effect of tillage in wheat on biomass accumulation (a), tillers density (b) and leaf area index (c) of wheat during 2012-13.

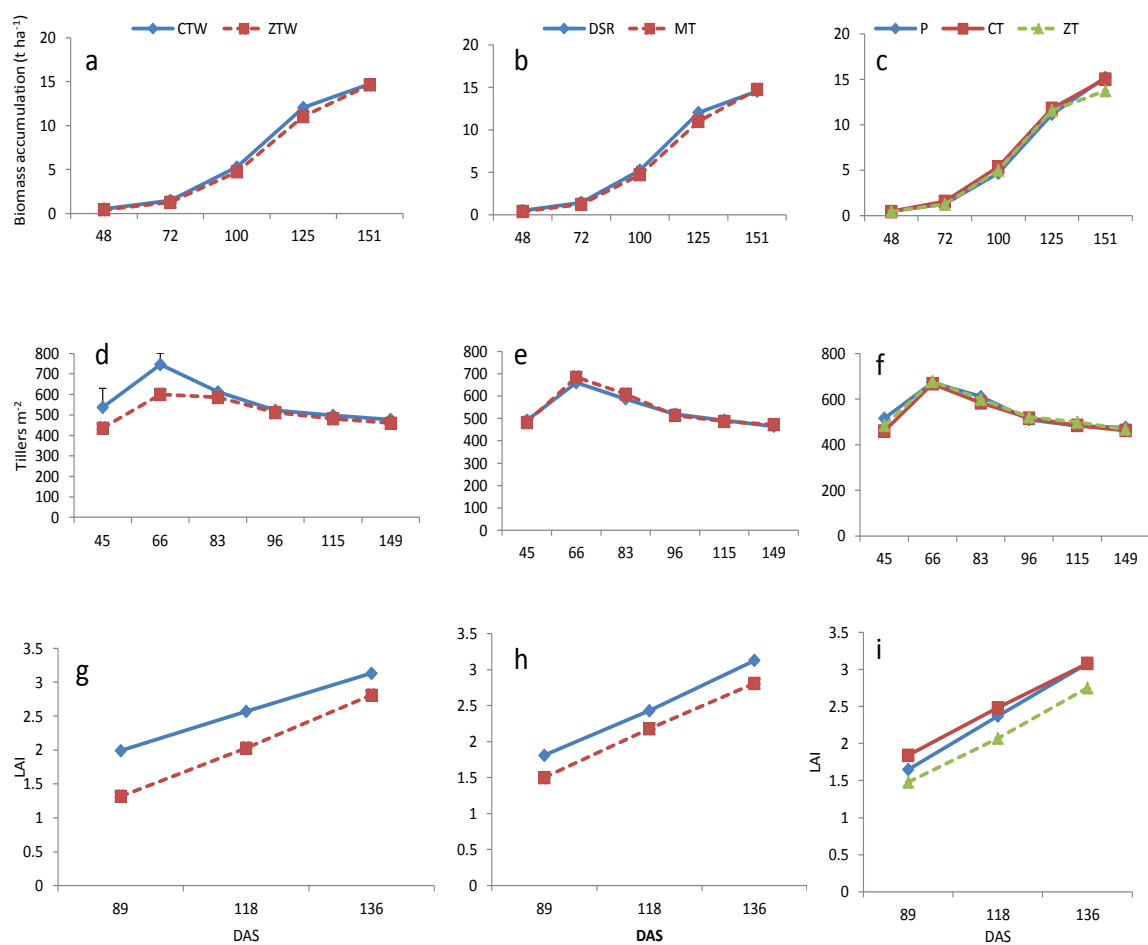


Fig. 3 Effect of tillage in wheat, rice establishment methods and tillage in rice on biomass accumulation (a-c), tiller density (d-f) and leaf area index (g-i) of wheat during 2013-14.

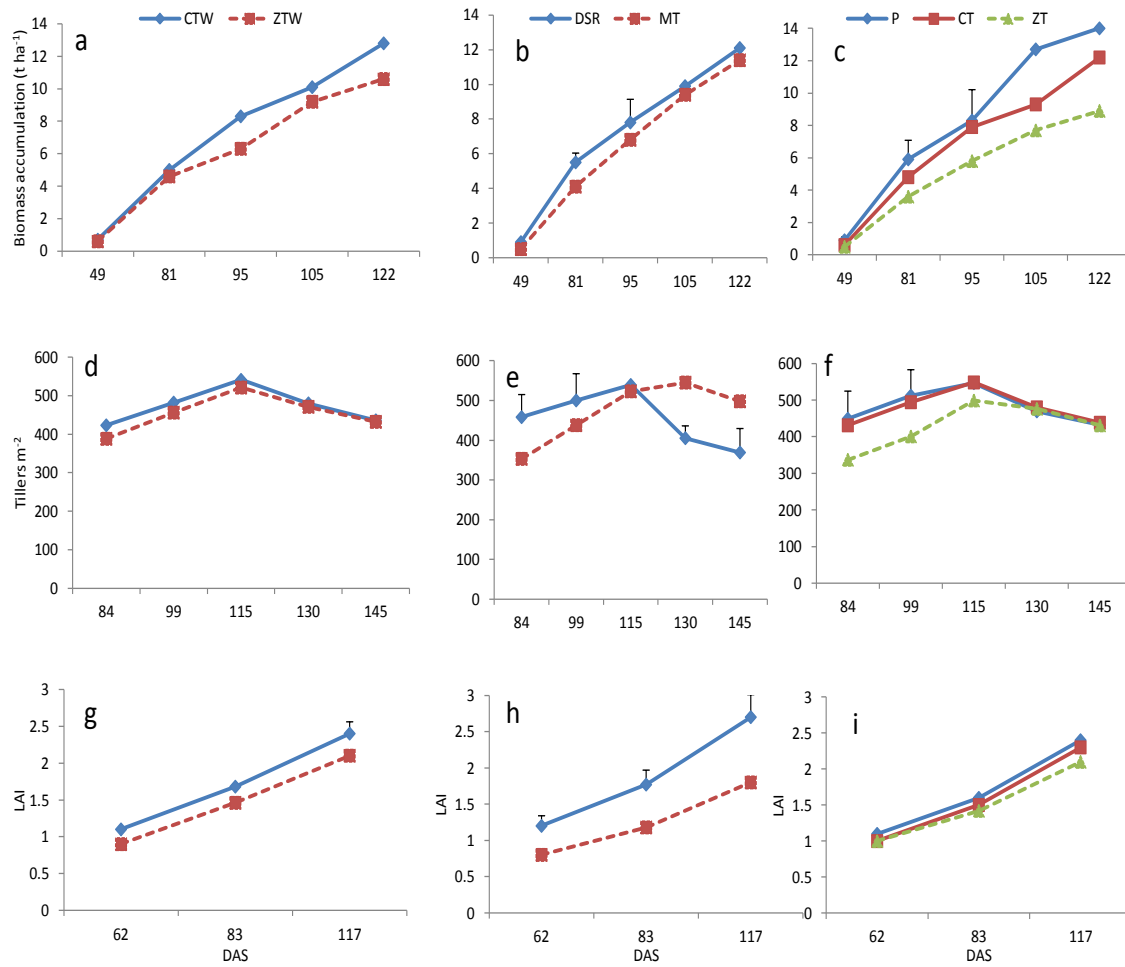


Fig. 4 Effect of tillage in wheat, rice establishment methods and tillage in rice on biomass accumulation (a-c), tiller density (d-f) and leaf area index (g-i) of rice during 2013.

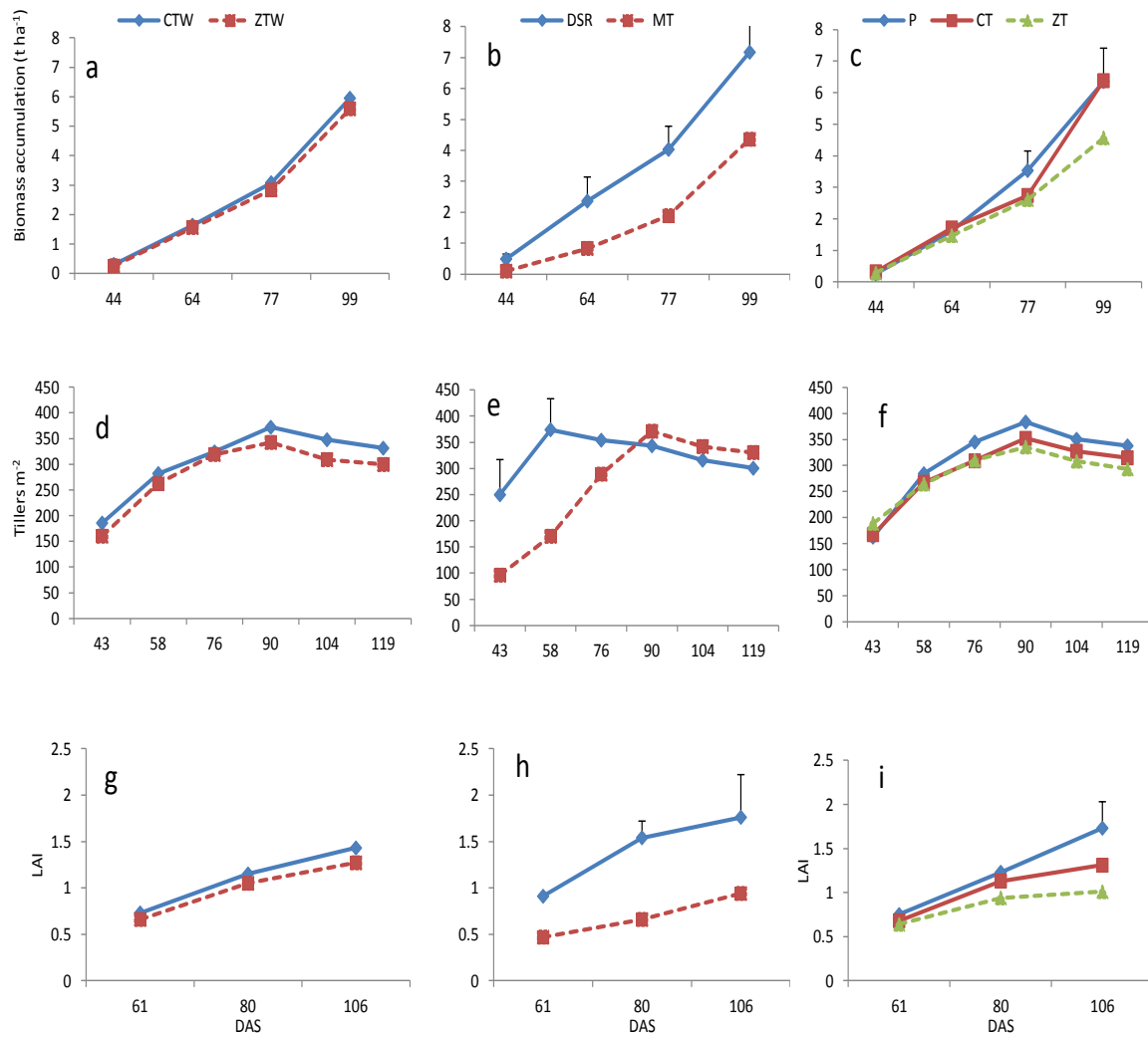


Fig. 5 Effect of tillage in wheat (a-c), rice establishment methods (d-f) and tillage in rice (g-i) on biomass accumulation, tillers density and leaf area index of rice during 2014.

Soil water balance and water productivity of wheat-direct dry seeded rice cropping system under conventional and zero-till conditions in semi-arid tropics of India

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ABSTRACT

Field experiments investigating the effects of different tillage methods on the soil water balance of irrigated wheat-rice cropping system were conducted during 2012–2014 in Punjab, India, on a sandy loam soil. The irrigation water consumption during wheat in 2013-14 was similar (331–348 mm) to that in 2012-13 (334-353 mm). In 2013-14, the effect of ZT in DSR was more pronounced in affecting $\Delta\theta$, being 42.5-47.1 mm in DSR-ZT plots in comparison to 54.3-54.5 mm in DSR-CT plots. The evapo-transpiration (ET) of wheat during 2012-13 was slightly higher (430-433 mm) to that in 2013-14 (401-430 mm). The evapo-transpiration losses in rice 2014 were higher (497-532 mm) than in 2013 (392-399 mm). The deep drainage of the system during 2012-13 was 40 per cent of the total input water used in the CTW plots with DSR-CT as compared to 30.4 per cent in ZTW plots. The corresponding values during 2013-14 were 33.8 per cent (CTW) and 28.7 per cent (ZTW), respectively. The evapo-transpiration (ET) losses of the wheat-rice cropping system were higher during 2013-14 (971-1057 mm) as compared to 2012-13 (908-922 mm). The irrigation water productivity (WP_i) of wheat-rice cropping system ranged from 0.56-0.74 g kg⁻¹ in 2012-13 compared to 0.45-0.54 g kg⁻¹ during 2013-14. During intervening period after wheat evaporation losses pragmatic to be higher in the ZTW plots as compared to the CTW plots as during 2012-13, ZTW plots on an average dried 7.6% and 12.8% higher than that of its counterpart plots. During both wheat 2012-13 and 2013-14, ZTW plots appeared to be wetter than the CTW plot throughout the soil profile up to 120 cm while during rice 2013 and 2014, the conventionally tilled plots observed to be wetter. Among the pure tillage systems CTW-DSRCT plots had highest irrigation water productivities (32.1 and 20%) during 2012 and 2014 than ZTW-DSRZT plots while among the mixed tillage systems ZTW-DSRCT plots had higher water productivities (17.8 and 4.4%) than the CTW-DSRZT plots during 2012-2014. Among the different tillage scenarios, irrigation (WP_i), total input (WP_{i+R}) and evapo-transpiration (WP_{ET}) based water productivity followed the order CTW-DSRCT > ZTW-DSRCT > CTW-DSRZT > ZTW-DSRZT.

Key words: Evapo-transpiration;Irrigation water productivity;Real water productivity;Soil matric potential

1. Introduction

The sustainable use of water is a critical issue against the backdrop of rising water demand for agricultural use as the world needs about 60% more food (FAO, 2013) to feed the 9.5 billion people in 2050 (United Nations, 2012). The scenario becomes much more challenging in the light of shrinking water resources (Singh and Panda., 2012a, Wani et al., 2012, Guan et al., 2015) due to urbanization, contamination, and climate change impacts. Furthermore, improved living standards (Mariolakos, 2007) and changing dietary habits, requiring more water, make the issue even more severe. The provision of irrigation is vital for achieving the food security for the ever- increasing global population (Singh, 2012a; Singh and Panda, 2012 b,c), particularly in arid and semiarid regions where water resources are critical for the economic development. The increased food production has to come from the available and limited water, land resources, which are finite as about 90% of the global consumptive water use is for irrigation (Scanlon et al., 2007; Siebert et al., 2010), and about 40% of the irrigation water is derived from groundwater (Siebert et al., 2010; Döll et al., 2011) which ultimately leads to its scarcity.

The majority of wheat and rice in the region being combine harvested, the farmers opt for easy and quicker way of disposing off the rice residues (>17 Mt year⁻¹) by burning thereby causing air pollution, loss of nutrients and degrading the soil health (Yadwinder-Singh and Sidhu, 2014). These residues if returned back into the soil could improve the deteriorating soil health apart from conserving and retaining moisture in the soil. The conservation tillage with an aim to retain crop residues on the soil surface may help in managing the environment as well as soil health.

Adopting proper tillage options can certainly solve the problem as residues on the surface act as mulch and help in water retention (Bhatt and Khera, 2006; Sharma et al., 1990), increase minimum and decrease maximum soil temperatures (Sidhu et al., 2007), increase water infiltration rate (Arshad et al., 1999), decrease evaporation, increase transpiration, crop yield and crop water productivity (Singh et al., 2011) as surface mulch partitions greater fraction of total ET towards higher productive transpiration component (Balwinder Singh 2011b).

Various resource conservation technologies (RCTs) viz. direct drilling of wheat with and without crop residues, direct seeded rice and mechanical transplanting of rice in conventional and zero till conditions, etc are being advocated for increased productivity, sustainability and profitability of RWCS as these primarily focus on conservation tillage and recycling of crop residues (Singh et al., 2011; Hobbs et al., 2008). Isolated studies (Rajesus et al., 2011), involving individual crops grown with RCTs, have indicated improved water productivities. Moreover, such studies are seldom based on systematic measurements of soil water balance components of crops grown with these RCTs (Humphreys et al., 2010; Kukal et al., 2014). The magnitude of the benefits of RCTs tends to be site-and situation-specific and cannot be generalized across the farming systems in different agro-climatic regions (Humphreys et al., 2010; Sudhir-Yadav et al., 2011; Sudhir-Yadav et al., 2014). Also the impact of RCTs with respect to establishment and tillage techniques on land and water productivity of the cropping system as a whole is not well documented in the literature (Devkotaa et al., 2015; Jat et al., 2014). The use of these RCTs in one crop may affect the performance and water productivities of other crop in the cropping system and/or negate the impacts of RCTs in the cropping system as otherwise observed in the individual crop.

Wheat-rice cropping system grown on an area of 17.5 M ha in north-west India is an important cropping system to ensure sufficient food for the huge current and projected population in the region. The availability and efficient use of water is a major obstacle in the way of boosting the productivity of wheat-rice system. The irrigated rice production require large amount of water (2500 lts for 1 kg of rice) (Bouman, 2009). The main rice and wheat producing states of India in semi-arid tropics- Punjab (5.0 M ha), Haryana (4.4 M ha) and western Uttar Pradesh (8.1 M ha). Are facing rapid decline of ground water table due to increased pumping out of water for rice-wheat cropping system, the average depth of ground water table in the central districts of Punjab had increased to 15-28 m by 2006 (Hira, 2009). It is predicted that by 2025, 42 out of 104 blocks (30% of Punjab) will have water table deeper than 30 m (G S Hira, personnel communication). The present study was thus conducted to evaluate the impact of non-conventional crop establishment techniques coupled with conservation tillage in wheat and rice on soil water balance components, profile water dynamics and water productivities of rice-wheat cropping system as a whole including the intervening period.

2. Material and methods

Field experiments were conducted during 2012-14 to study the soil water balance components, profile water dynamics and water productivities of rice-wheat system under different tillage and establishment methods at the research farm of Punjab Agricultural University, Ludhiana, India.

2.1 Location and climate

The research site is located is situated in the central plain region of Punjab, India (Trans-Gangetic Zone) at 30°54' N latitude and 75°98' E longitude at an altitude of 247 m above the mean sea level. The climate of the region is subtropical, semi-arid with very hot and dry summers (April-June), wet monsoon season (late June to mid-September) and a cool dry winter (October-February). The mean minimum and maximum temperatures show considerable fluctuations during summer and winter months. Maximum air temperature above 38°C is common during summer, whereas frequent frosty spells are experienced in December-January. The average annual rainfall of the region is 650-700 mm and a greater portion (about 75 percent) of this rain is received during summer monsoon period (July to September), while in winter a few showers of cyclonic rains are received between December and January.

2.2 Weather during the study period

The maximum temperature during March-May was slightly higher in 2012-13 than in 2013-14 and the long-term average maximum temperature. It reversed during June-October being lower in 2012-13 than in 2013-14 and long term average, particularly in the months of September and October. However, the minimum temperature was almost similar during 2012-13 and 2013-14, being slightly higher than the long term average during June-July and October (Fig. 1a). The pan evaporation in general was lower during both the years than the long term average. However, it was higher during June-September in 2013-14 than in 2012-13 and the long term average (Fig. 1b). The total amount of rainfall was higher (891.6 mm) in 2012-13 than in 2013-14 (582.3 mm) (Fig. 1c). However, the rains were better distributed during 2013-14 (42 rainy days) than during 2012-13 (31 rainy days). The month of June recorded abnormally higher rainfall (296.4 mm) during 2012-13 compared to 30.3 mm during 2013-14 (Fig. 1d).

2.3 Study soil characteristics

The experimental site was under puddle transplanted rice for the last 20 years

except that the field was under direct dry-seeded rice (DSR-CT) sown under tilled conditions during the immediate previous year (2012). The experimental soil was sandy loam (sand 65-68%, clay 11-3%), neutral to slightly alkaline, non-saline and medium in soil organic carbon (0.44%) in the surface layer (Table 1). The soil had a sub-surface compact layer (bulk density of 1.74 Mg m^{-3} at 15-30 cm). The available nutrients (N, P and K) were in the medium range. The depth to the ground water at the site was around 24 m and the quality of water was good for all crops.

2.4 Treatment details

The laser levelled field was laid out as per the treatments with wheat grown conventionally (CTW) and with zero tillage (ZTW) with straw load of 4.4 t ha^{-1} retained at the surface. After wheat harvest, the main plots were split into two sub-plots to impose different sub-plot treatments viz. direct seeded rice (DSR) and mechanically transplanted rice (MTR). The sub-plots were further split into three sub-sub plots for allocating the sub-sub plot treatments of tillage in rice viz. puddled (P), conventional-(CT) and zero- tillage (ZT). The treatments were replicated thrice in split-split plot design. The rice and wheat crops were irrigated on the basis of soil matric potential (20 kPa at 20 cm depth) using electronic tensiometers installed in each plot. The irrigation water amount was measured for each plot by digital flow meter installed at the mouth of the plot.

2.6 Measurement of soil water balance components

The irrigation water amount (mm) was measured using digital flow meter installed at the mouth of each plot to a depth of 5 cm in wheat and 7.5 cm in rice during each irrigation. Rain fall amount (mm) was determined on the rainy day using rain gauge installed at the experimental site, itself.

The evaporation from the soil surface of growing crop was measured using mini-lysimeter which consisted of two cylindrical PVC tubes. The outer tube was 0.16 m in diameter and 0.20 m long, whereas the inner tube was 0.10 m in diameter and 0.20 m long. The inner tube was covered by porous end cap at the bottom end, whereas the outer was open at both the ends. The undisturbed soil cores were obtained in the inner PVC tube at weekly interval and immediately after every irrigation/rainfall during rice season. The weight of the inner tube placed in the outer tube along with end cap, was recorded daily at 0900 hours. The above ground

portion of any small weeds that may have been growing in the mini-lysimeters was removed.

The daily deep drainage was recorded by installing tensiometers at 45 and 60 cm for rice (assuming rhizosphere of 50 cm) and 90-120 cm for wheat (Assuming rhizosphere of 100 cm for wheat). Using unsaturated hydraulic conductivity of the transitional layer the flux was calculated on daily basis and expressed as deep drainage.

The seepage of water during rice season was calculated from the difference in water level in the whole plots and infiltration rings embedded till the hardpan to a depth of 30 cm during flooding.

The moisture content of the profile (at depth interval of 0-15, 15-30, 30-60, 60-90, 90-120 and 120-150 cm) were measured thermo-gravimetrically before sowing and after harvesting of each crop. The moisture content was then expressed in mm of water and added up for each layer to obtain profile moisture storage.

2.7 Water productivities

The water productivities were measured in term of irrigation water productivity (WP_I), ratio of the recorded grain yield ($Mg\ ha^{-1}$) to the total amount of applied irrigation water (mm); total input water productivity (WP_{I+R}), ratio of grain yield ($Mg\ ha^{-1}$) to the sum of irrigation water and the rainwater amount (mm); and ET based water productivity (WP_{ET}), ratio of grain yield ($Mg\ ha^{-1}$) to the total water lost as evapo-transpiration (mm).

3. Results and discussion

3.1 Soil water balance

3.1.1 Wheat

The irrigation water consumption during 2013-14 was similar (331–348 mm) to that in 2012-13 (334-353 mm) was similar in ZTW and CTW plots in 2013-14 except in double zero-till plots (ZTW-DSRZT) where the irrigation water amounts was sufficiently lower (270 mm) than all other treatment combinations (341-348 mm) (Table 2). The lower amount of irrigation water consumed in ZTW-DSR-ZT scenario was due to the poor crop stand leading to lower uptake of water from the soil. The amount and distribution of rainfall during the two wheat seasons was almost similar.

The change in profile moisture was higher (61.6-78.2 mm) in 2012-13 than in 2013-14 (42.5-54.5 mm), thereby indicating higher use of profile water by wheat crop during first year. In 2012-13, zero tillage in wheat resulted in higher change in profile moisture ($\Delta\theta$) (or in other words, zero-till plots used more profile water than CT plots). It could be due to the higher evaporation from zero-till plots with continuity of the capillaries especially in the surface layers. However, in 2013-14, the effect of ZT in DSR was more pronounced in affecting $\Delta\theta$, being 42.5-47.1 mm in DSR-ZT plots in comparison to 54.3-54.5 mm in DSR-CT plots (Table 2), perhaps due to the similar reasons.

The evapo-transpiration (ET) of wheat during 2012-13 was slightly higher (430-433 mm) than that in 2013-14 (401-430 mm) (Table 2). It could be due to higher maximum and minimum temperatures during 2012-13 compared to 2013-14. The ET of wheat grown with zero- and conventional-tillage was similar, during 2012-13. However, during 2013-14, zero tillage in both during wheat and rice lowered the ET of wheat mainly because of poor crop biomass in double zero till plots leading to lower uptake and transpiration of water by the crop canopy.

3.1.2 Rice

The irrigation water used was sufficiently higher during 2014 (1526-1651 mm) than in 2013 (991-1021 mm) with 323 mm of rainfall split over 17 wet days with 462 mm rain spread over 16 rain events (Table 2). The irrigation water consumption was similar in different tillage scenarios during 2013 but in 2014, shifting from conventional tillage to mixed tillage or double zero tillage system resulted in higher irrigation water consumption. This is in contrary to the reports published in the literature on this aspect (Jat *et al* 2014). It could be due to the reason that in the present study, zero till DSR plots had no straw mulch retained on the soil surface.

The change in profile moisture storage at sowing and harvest of rice was not so conspicuous as in wheat, perhaps due to frequent irrigations in rice crop as compared to the wheat crop. The lower seepage losses during 2013 (265-462 mm) as compared to 2014 (561-732 mm) could be due to the lower irrigation water amount consumption during 2013. In double ZT system viz. ZTW-DSRZT, seepage was higher (35.7% during 2013 and 16.4% during 2014) as compared to the conventional system viz. CTW-DSRCT (Table 2). The zero tillage in wheat increased the seepage

losses in DSR under both ZT and CT system, the increase being higher in DSR-CT than in DSR-ZT.

The deep drainage losses during rice season beyond 60 cm were to the extent of 36-54% of the total input water used during the crop season (Table 2). During both the years, the deep drainage losses were lower in plots with zero tillage in wheat, but zero tillage in DSR resulted in higher deep drainage losses. Sudhir Yadav et al (2011b) reported that in clay loam soil, the lower irrigation input to DSR than in PTR, was due to reduced seepage and drainage losses. They further reported that 30–50% reduction in irrigation water while shifting from continuous flooding to intermittent irrigation was due to significant reduction in drainage losses.

The evapo-transpiration losses in rice were higher (497-532 mm) during 2014 than in 2013 (392-399 mm). However, the ET losses of DSR were not affected by tillage both in rice and wheat. The ET constituted 27 % of the total input water used during both the years. The poor co-relation coefficient ($R^2=0.12$) between ET and grain yield of rice indicates that despite of the lower grain yield under zero-till conditions, the ET of the crop did not decrease. This could be due to that fact that despite of lower grain yields, the higher weed population in zero-till plots consumed water for transpiration purposes leading to similar or even higher ET under zero-till conditions.

3.1.3 Wheat-rice system

The total input water for wheat-rice cropping system was higher (2330-2467 mm) during 2014 compared to 1955-1993 mm during 2013 (Table 2). As explained earlier, higher rainfall of 173 mm during 2013 resulted in lower irrigation amounts. The tillage in wheat and rice did not affect the total input water of the cropping system during both the years (Fig. 2).

The deep drainage and seepage in the wheat-rice cropping system was affected by zero tillage in wheat. The deep drainage of the system during 2012-13 was 40% of the total input water used in the CTW plots with DSR-CT as compared to 30.4% in ZTW plots (Fig. 2). The corresponding values during 2013-14 were 33.8 per cent (CTW) and 28.7% (ZTW), respectively. Similar was the trend in DSR-ZT plots. The tillage in rice in CTW plots did not affect deep drainage during both the years but in ZTW plots, the zero tillage in rice increased deep drainage as compared to the conventional tillage. Zero tillage in wheat resulted in higher seepage losses

(462-732 mm) compared to the conventional tillage (284-561 mm) during both the years (Fig. 2). The seepage losses were lower with zero tillage as compared to CT in rice (DSR-CT).

The evapo-transpiration (ET) losses in wheat-rice cropping system were higher during 2013-14 (971-1057 mm) than in 2012-13 (908-922 mm), which was due to the higher amount of rain (39%) during 2012-13 (Fig. 2). However, the ET of wheat-rice cropping system including the intervening period was not affected by tillage in wheat or in rice.

3.2 Water productivities of wheat-rice system

3.2.1 Irrigation water productivity

The irrigation water productivity (WP_I) of wheat-rice cropping system ranged from 0.56-0.74 g kg⁻¹ in 2012-13 compared to 0.45-0.54 g kg⁻¹ during 2013-14. The lower values of WP_I during 2013-14 are due to the lower amounts of rains during the year, leading to consumption of higher irrigation water amount (Fig. 3). Shifting from conventional to zero-till system, resulted in decrease in WP_I being lowest in double zero-till system (0.56 g kg⁻¹ during 2012-13 and 0.45 g kg⁻¹ during 2013-14). The WP_I of zero-till rice in CTW plots was almost similar to that in plots with double zero till. Zero tillage in wheat resulted in lower (18%) WP_I compared to the conventional system viz. CTW-DSRCT during 2012-13. This difference decreased to 13% during 2013-14.

On an average in the rice-wheat cropping system as a whole including the intervening period consumed 42% higher irrigation water during 2013-14 than in 2012-13 (Fig. 3). Further, among different tillage scenarios, the irrigation water amount varied as: ZTW-DSRCT (48.3%) > CTW-DSRZT (43.5%) > CTW-DSRCT (39.7%) > ZTW-DSRZT (35.6%) (Fig. 3).

3.2.2 Input water productivity

The input water productivity (WP_{I+R}) of wheat-rice cropping system decreased by 34.2% in 2012-13 while shifting from complete conventional tillage system to complete zero tillage system. However, this difference decreased to 22.2% in 2013-14. The WP_{I+R} of the tillage systems with either single or double zero tillage was almost similar during 2013-14.

The rainfall during 2012-13 was higher (39%) than in 2013-14. The double ZT plots (ZTW-DSRZT) recorded lowest input water productivity during both the years (0.38 g kg⁻¹ during 2012-13 and 0.36 g kg⁻¹ during 2013-14) (Fig. 3). Further, it was observed that CTW-DSRZT, ZTW-DSRCT and CTW-DSRCT had 7.9, 18.4 and 34.2% higher input water

productivity over the ZTW-DSRZT plots during 2012-13 and the differences decreased to 3.0, 8.3 and 22.2% during 2013-14.

3.2.3 Real water productivity

The real water productivity based on evapo-transpiration (WP_{ET}) (Fig. 3) ranged from 0.83-1.08 g kg⁻¹ in 2012-13 to 0.86-1.02 g kg⁻¹ in 2013-14. The differences in real water productivity among various tillage scenarios narrowed down during 2013-14, being similar in the treatments with single or double zero tillage. The results indicate that during harsh weather conditions, the differences in WP_{ET} were not so conspicuous among various tillage scenarios.

The double ZT plots (ZTW-DSRZT) had lowest WP_{ET} (0.76 g kg⁻¹) during 2012-13 while it slightly improved over CTW-DSRZT plots (0.86 g kg⁻¹) during 2013-14. The CTW-DSRZT, ZTW-DSRCT and CTW-DSRCT plots had 7.2, 18.1 and 30.0% higher WP_{ET} as compared to the double ZT plots while during 2013-14, the ZTW-DSRZT, ZTW-DSRCT and CTW-DSRCT plots had 1.1, 3.4 and 18.6% higher WP_{ET} as compared to the CTW-DSRZT plots (Fig. 3).

3.3 Profile water dynamics

3.3.1 Wheat

The soil matric potential (SMP) during 2012-13 measured at 10 cm soil depth from 40 days after sowing (DAS) onwards was similar in both CTW and ZTW plots till 50 DAS (Fig. 4a). Later the CTW plots started drying at faster rate as compared to zero-till plots till harvest. At 20 cm soil depth, the SMP profiles till 63 DAS and thereafter indicates that the zero till plots retained higher moisture than CTW plots (Fig. 4b). From 78-119 DAS, the moisture status in the two tillage systems was similar, but thereafter, the CT plots dried at a faster rate. At 30 and 45 cm soil depth during 2012-13, the SMP was similar in the two treatments (Fig. 4c,d), whereas at 60 cm, the CTW plots behaving similarly to ZTW plots till 78 DAS, dried at a faster rate thereafter (Fig. 4e). Interestingly at 90 cm soil depth, the CTW plots dried faster than ZTW plots throughout the growing season (Fig. 4f). These fluctuations in SMP during 2012-13 at different soil depths indicate that zero tillage affected both the upward as well as downward movement of soil water into the soil. The continuity of the capillaries in zero-till plots could have resulted in upward movement of water into surface layer of plots. The presence of rice straw @ 4.4 t ha⁻¹ could be another reason for the higher wetness in the zero-till plots. Balwinder singh *et al* (2011b) in clay loam soil reported that mulch suppressed whole season soil evaporation by 35–40 mm in irrigated wheat and resulted in higher soil wetness in mulched than in unmulched plots. Similar observations

were recorded with respect to SMP at different soil depths during 2013-14, except that at 90 cm the wetness of soil in all the tillage scenarios was almost similar unlike as in 2012-13 (Fig. 5).

3.3.2 Rice

The SMP profiles at different depths (Fig. 9) during 2013 indicate that the double zero till plots dried faster in the surface layer (10 cm) (Fig. 6a). The SMP did not vary much with respect to different tillage scenarios in the sub-surface layers (15-60 cm) (Fig. 9 b-d) perhaps due to frequent irrigations to DSR plots. However, during initial stages (43-51 DAS), double zero till plots had lowest moisture status among all the tillage scenarios except CTW-DSRCT plots, in which the moisture status was similar to that in double zero till plots. Similar trend was observed in soil matric potential recorded at different depths during 2014 (Fig. 7). The zero till plots are expected to dry at a faster rate due to continuity of soil pores in these plots. This is evidenced from the evaporation measured during the rice season, which was sufficiently higher (36% in 2013 and 22% in 2014) in complete zero till system than in conventional tillage in DSR plots (Fig. 8).

3.3.3 Intervening period between wheat and rice

The soil matric potential profiles recorded immediately after wheat harvest till rice sowing (Fig. 9 and 10) clearly indicate that zero-till plots dried faster compared to the conventionally tilled plots during both in 2013 and 2014. The drying was higher (28%) in 10 cm soil layer (Fig. 9a) than in 20 and 30 cm (18%) layers during 2013 (Fig. 9b, c). The corresponding values during 2014 were 21% at 10 cm soil depth (Fig. 10a) compared to 16-17% in lower soil layers (Fig. 10b, c). This is further substantiated by higher evaporation (7.6% in 2013 and 12.8% in 2014) throughout the period (Fig 11) in ZTW plots. In 2014, the soil matric potential fluctuate during intervening periods after wheat harvest due to the four rain events occurring during this period. In general, the zero-till plots (without straw load) had higher soil temperature, soil matric potential, higher evaporation losses during the period.

4. Conclusions

Direct drilling of wheat in standing rice stubbles (ZTW) conserved the soil moisture and decreased the soil temperature. The MTR had higher water productivities under all the rice tillage methods than DSR. The total input water consumed and evapo-transpiration of wheat-rice cropping system including the intervening period were similar (within a particular year) under different tillage and crop establishment scenarios. The ET of wheat-rice cropping system in 2013-14 was higher (971-1051 mm) than in 2012-13 (908-922 mm). In general, the zero tilled plots were wetter than conventionally tilled plots

at all the soil depths (0-120 cm) during wheat season. Double ZT plots partitioned higher fraction of input water towards the ET component but not depicted in grain yields and water productivities because of recorded significantly higher weed pressure. Among different rice-wheat cropping scenarios, irrigation (WP_I), total input (WP_{I+R}) and evapo-transpiration (WP_{ET}) based water productivity followed the order CTW-DSRCT > ZTW-DSRCT > CTW-DSRZT > ZTW-DSRZT.

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Table 1 Basic physico-chemical properties of the studied site

Depth (cm)	Sand (%)	Clay (%)	pH (2:1)	EC (2:1)	O.C (%)	Available nutrients (kg ha ⁻¹)			Db (Mg m ⁻³)	Moisture content (%w/w)	
						N	P	K		F.C (0.3 bar)	P.W.P (15 bar)
						341.2	15.2	250.8	1.66	11.3	7.7
0-15	64.7	11.3	7.26	0.25	0.45					10.4	6.2
15-30	65.9	11.3	7.23	0.31	0.44	332.8	14.2	218.6	1.74	12.1	6.4
30-60	66.8	12.6	7.31	0.32	0.35	--	--	--	1.59	11.3	6.7
60-90	67.6	12.7	7.18	0.26	0.37	--	--	--	1.63	12.1	7.3
90-120	68.2	12.3	7.01	0.34	0.34	--	--	--	1.57	12.5	6.6
120-150	68.8	11.9	7.08	0.33	0.32	--	--	--	1.61		

Table 2 Soil water balance components of wheat and rice during 2012-14

2012-13								
	Wheat (158 mm; 12)			Rice (462 mm; 16)				
	I+R	ET	Δθ	I+R	ET	Δθ	S	D
CTW-DSRCT	492	430.4	61.6	1457	391	2.20	284.0	780.0
CTW-DSRZT	--	--	--	1483	399	1.42	265.1	817.5
ZTW-DSRCT	--	--	--	1453	391	1.74	461.6	599.0
ZTW-DSRZT	511	432.8	78.2	1476	396	2.20	385.3	692.2
2013-14								
	Wheat (124 mm; 12)			Rice (323 mm; 17)				
	I+R	ET	Δθ	I+R	ET	Δθ	S	D
CTW-DSRCT	455	400.7	54.3	1849	497	2.13	561.0	788.8
CTW-DSRZT	472	429.5	42.5	1919	517	1.37	579.7	821.2
ZTW-DSRCT	466	411.5	54.5	1974	532	1.44	731.7	709.3
ZTW-DSRZT	394	346.9	47.1	1907	513	1.82	653.3	738.8

**Figures in parenthesis are the rainfall amounts and number of rainy days*

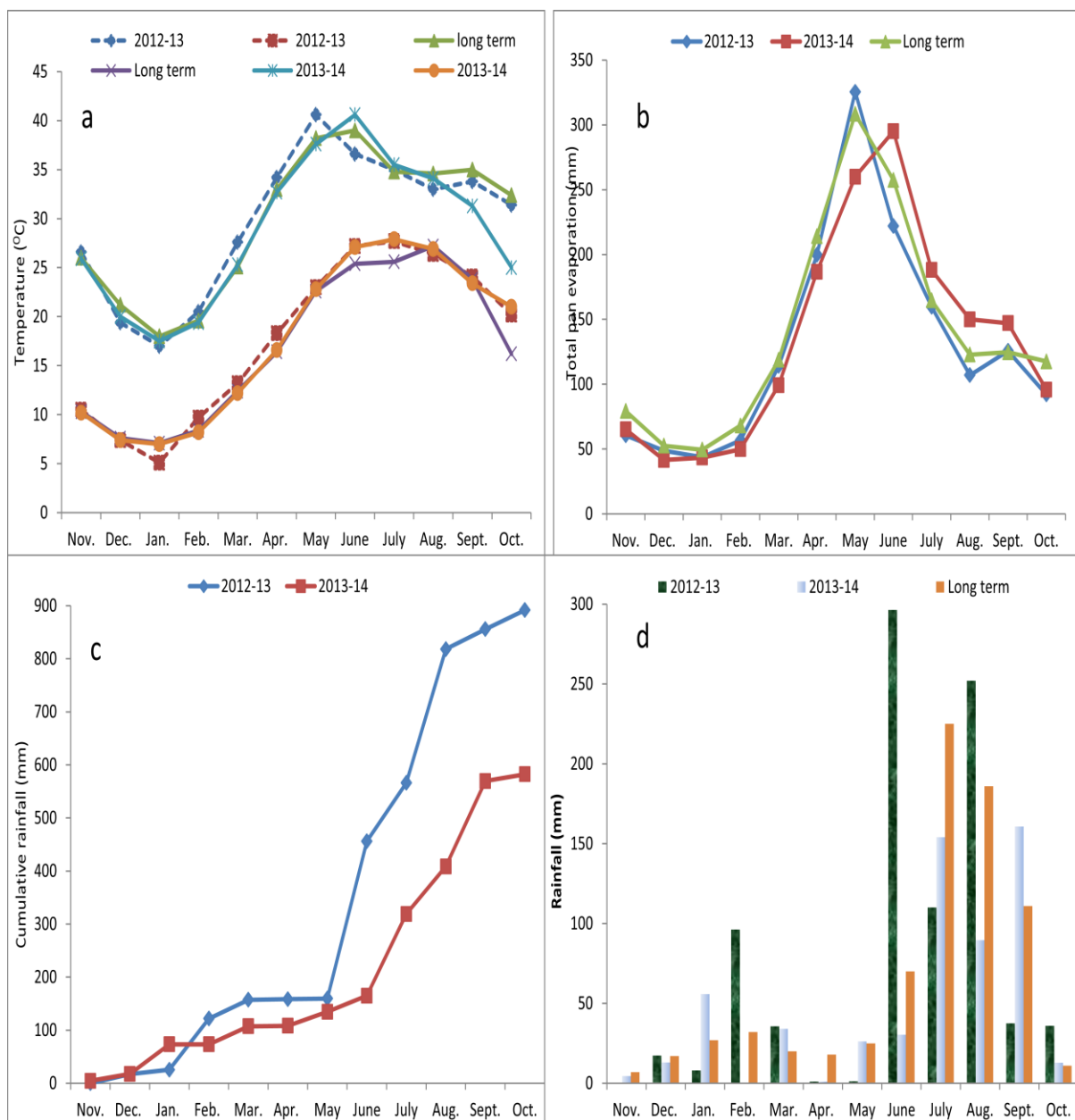


Fig.1 Mean monthly maximum and minimum temperatures (a), pan evaporation (b), cumulative rainfall (c) and monthly rainfall distribution (d) during the study period (2012-14).

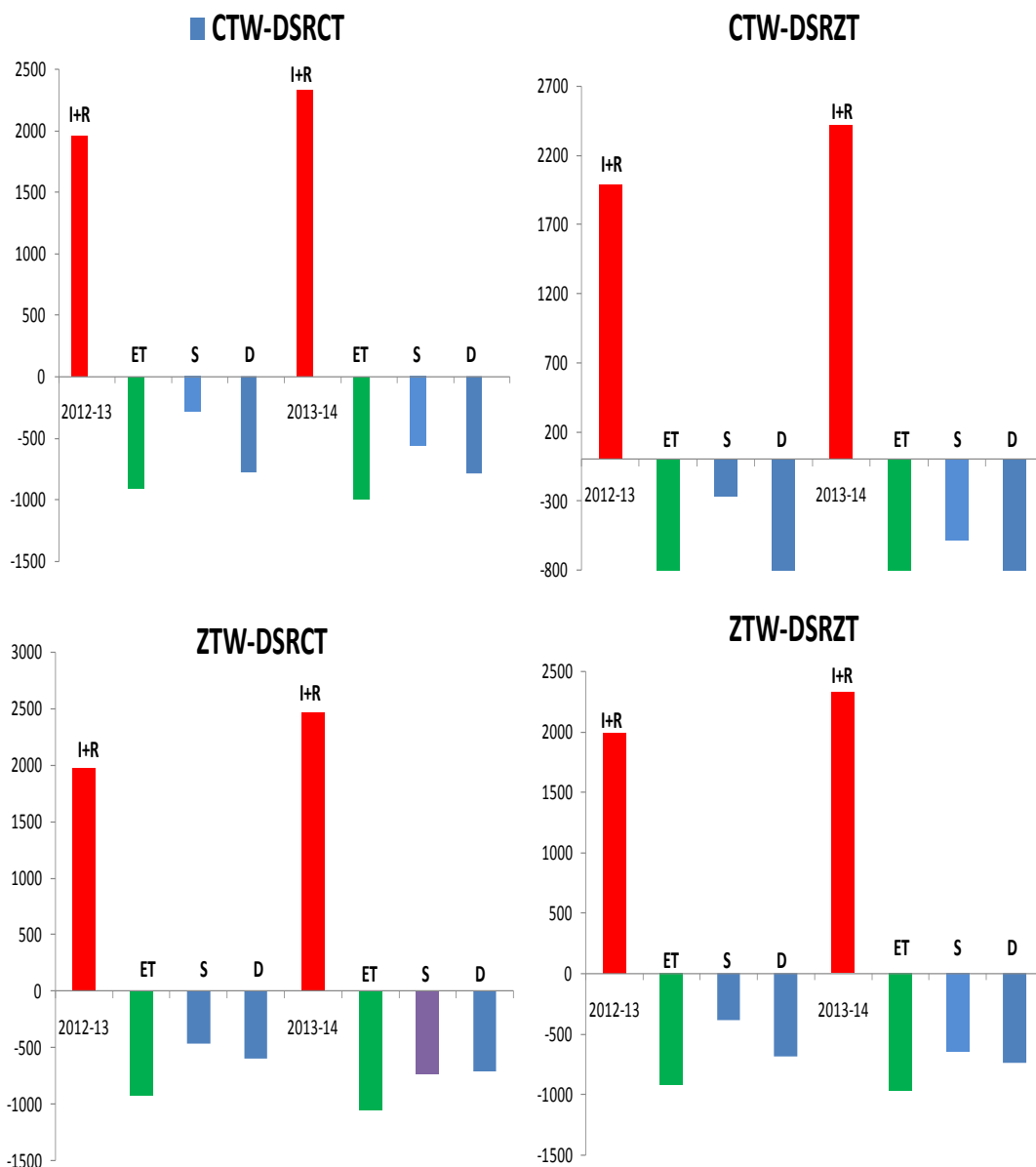


Fig 2 Water balance components (mm) of wheat-rice system including intervening period as affected by different tillage methods (*I+R* denotes irrigation+rain, *S* denotes seepage, *D* denoted deep drainage and *ET* denotes evapo-transpiration)

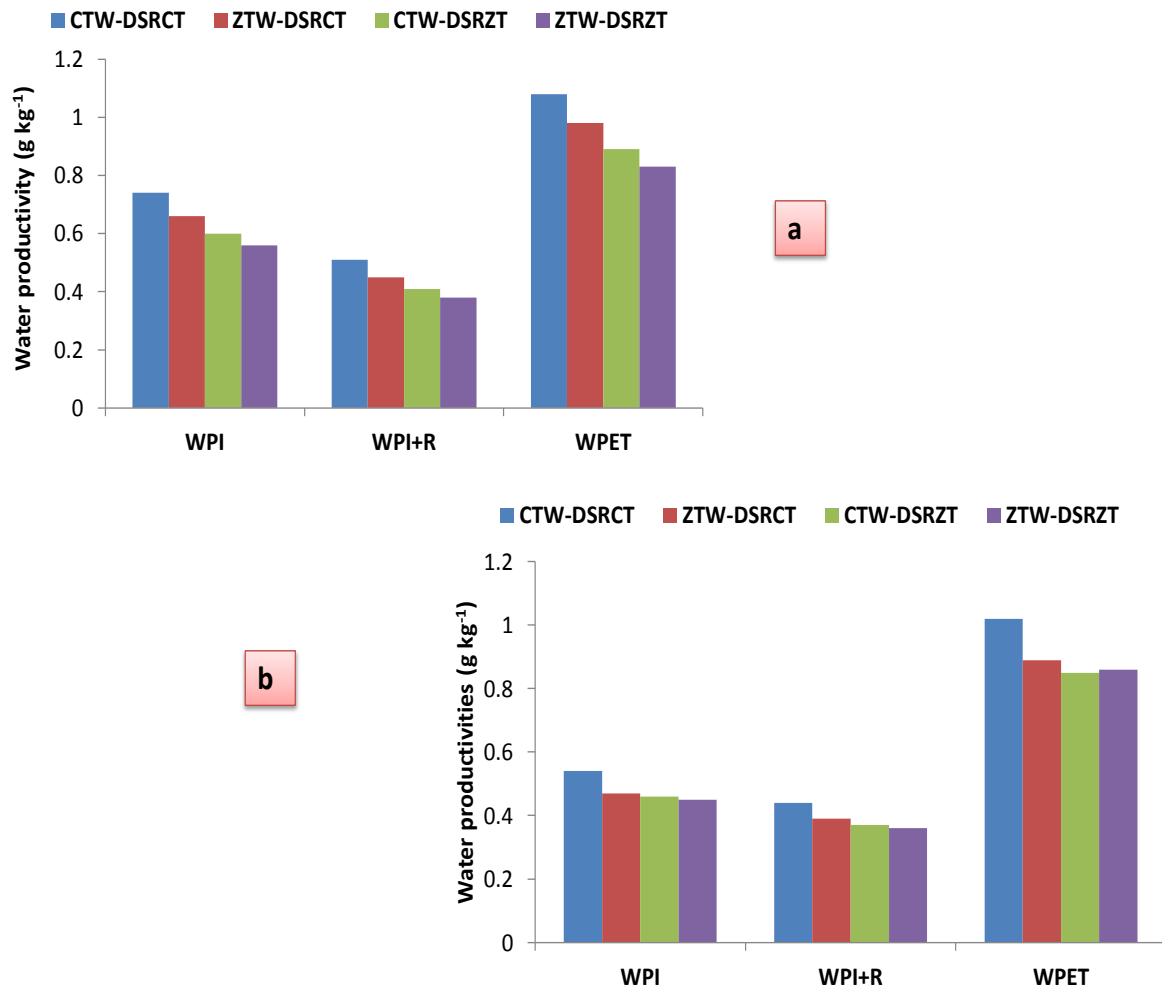


Fig. 3 Irrigation(WP_I), input (WP_{I+R}) and real (WP_{ET}) water productivity as affected by different tillage methods during (a) 2012-13 and (b) 2013-14

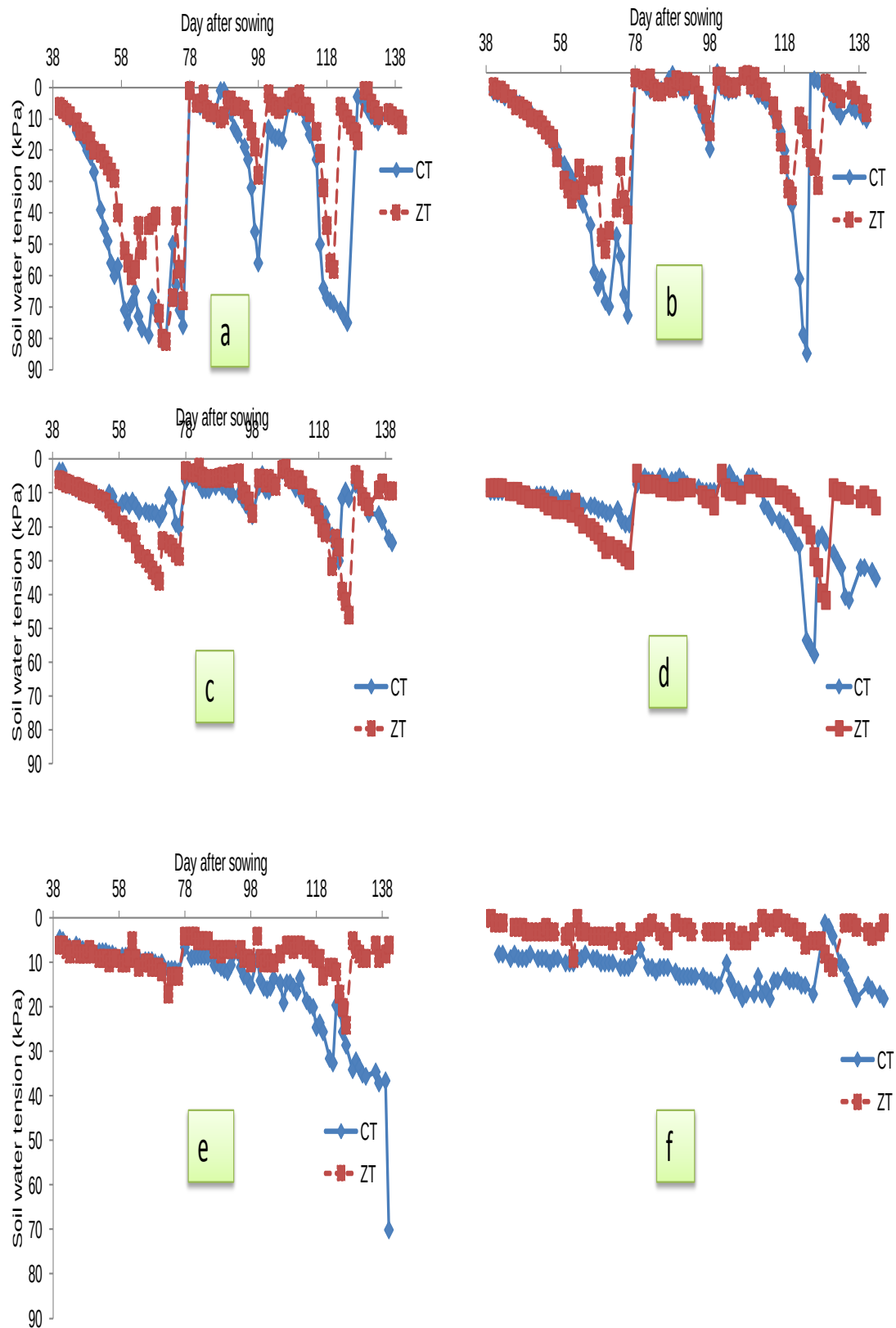


Fig. 4 Soil matrix potential at (a) 10, (b) 20, (c) 30, (d) 45, (e) 60 and (f) 90 cm soil depth in relation to conventional and zero tillage in wheat during 2012-13

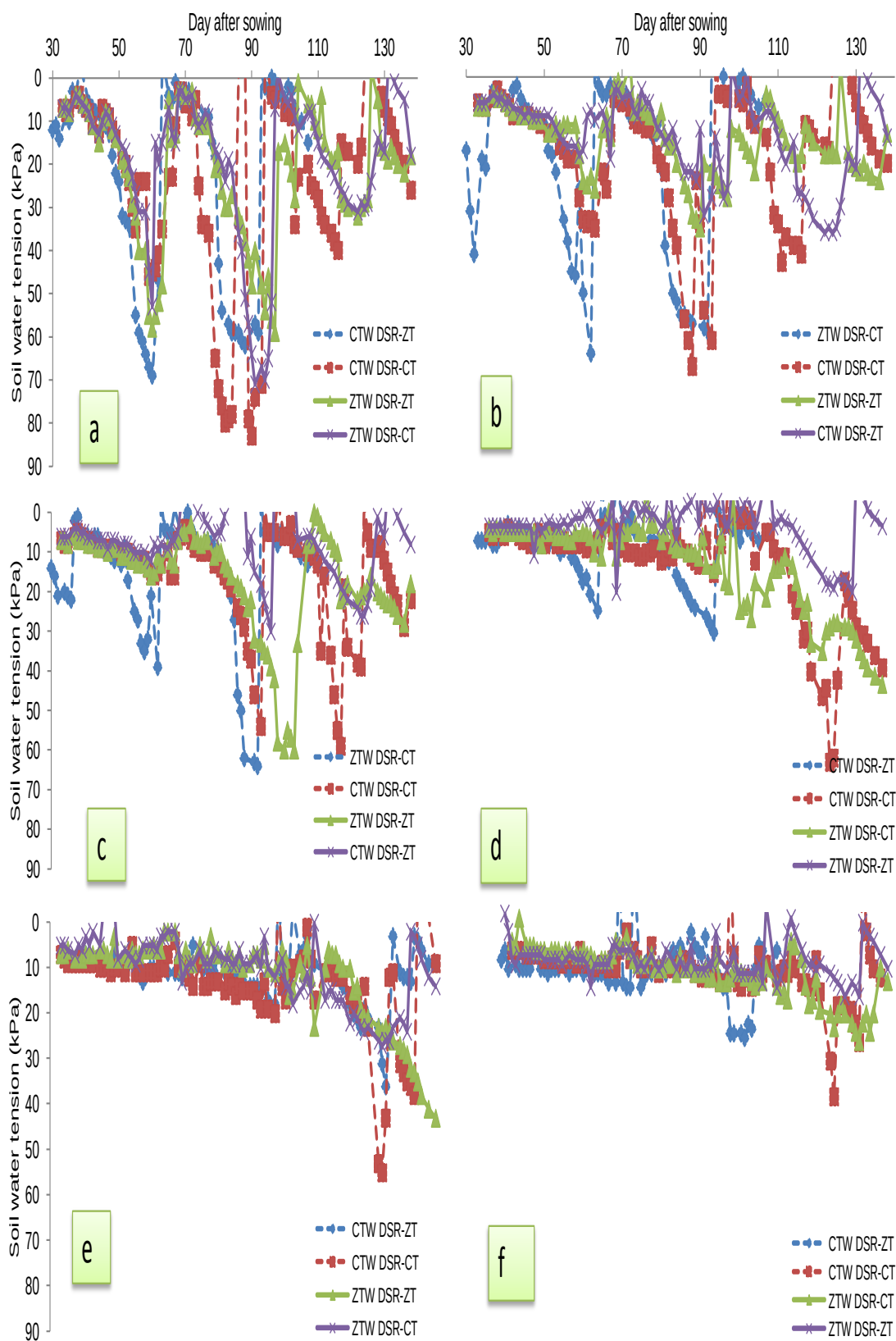


Fig. 5 Soil matrix potential at (a) 10, (b) 20, (c) 30, (d) 45, (e) 60 and (f) 90 cm soil depth in relation to conventional and zero tillage in wheat during 2013-14

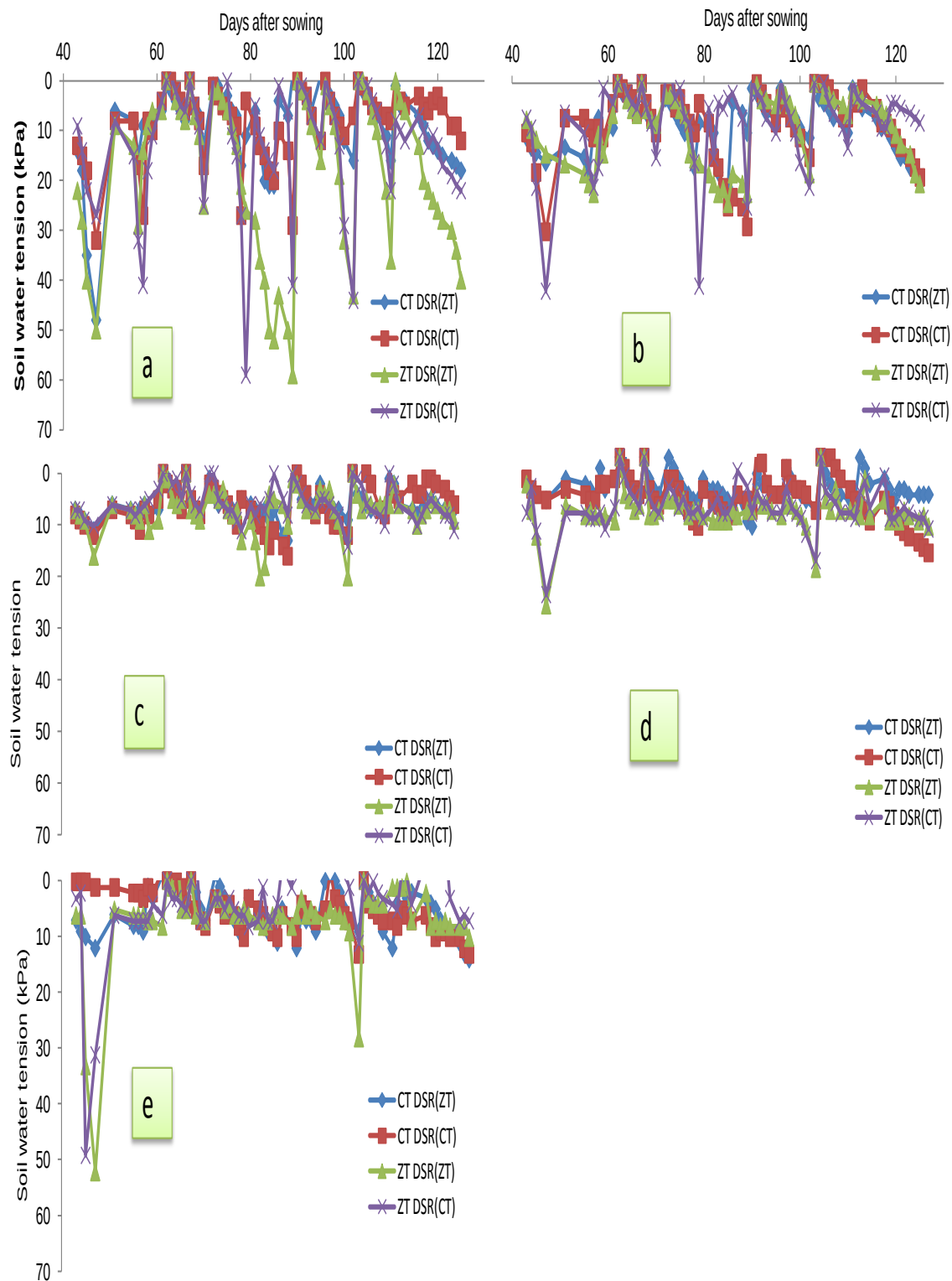


Fig. 6 Soil matrix potential at (a) 10, (b) 15, (c) 30, (d) 45 and (e) 60 soil depth in relation to conventional and zero tillage in rice 2013

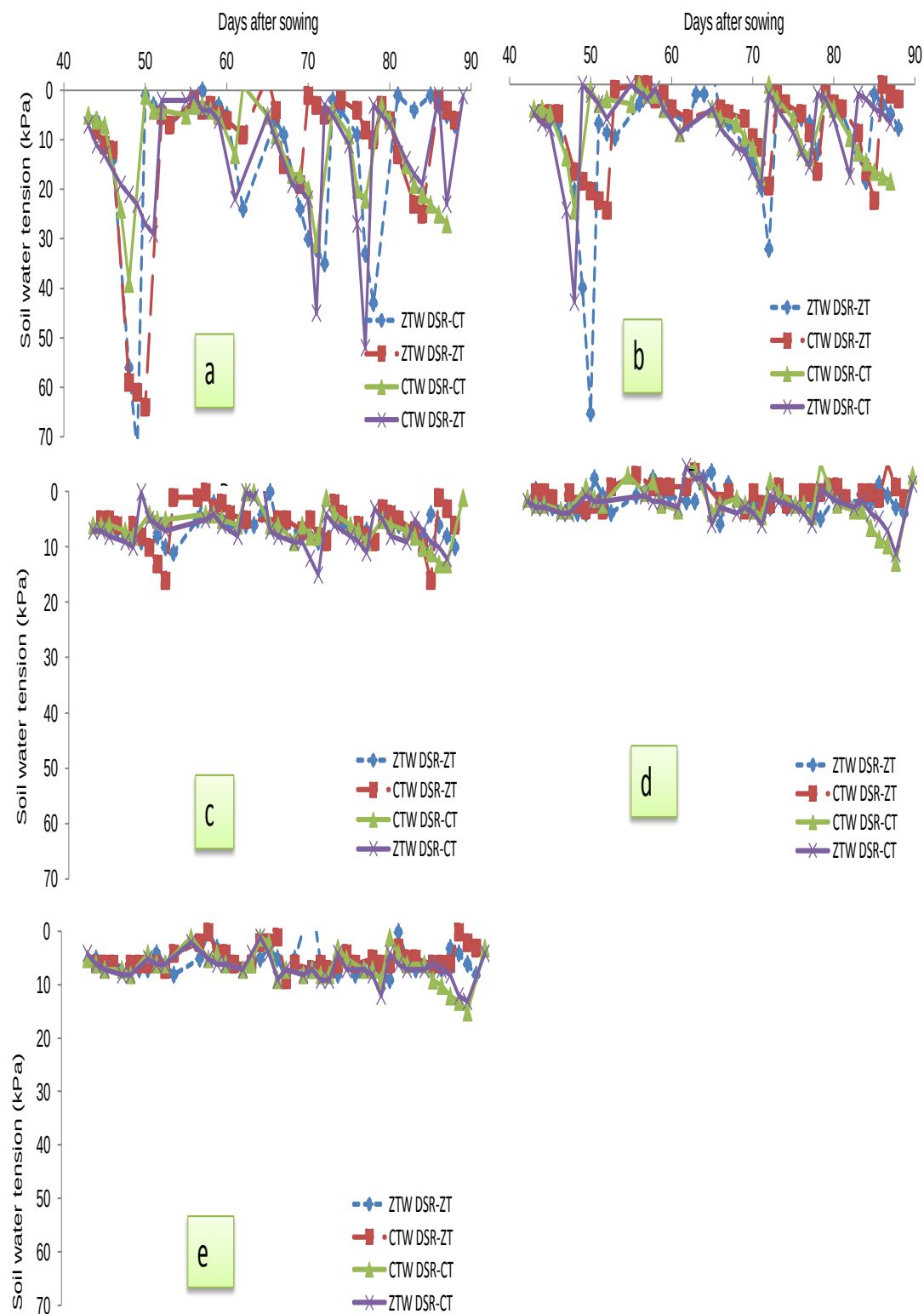


Fig. 7 Soil matrix potential at (a) 10, (b) 15, (c) 30, (d) 45 and (e) 60 soil depth in relation to conventional and zero tillage in rice 2014

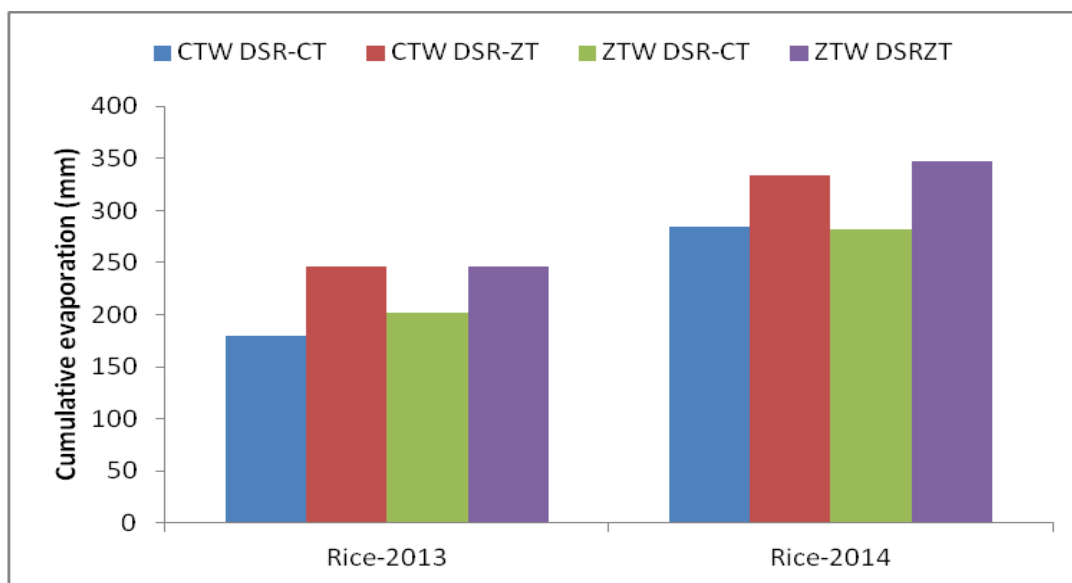


Fig. 8 Evaporation losses under different tillage scenarios in rice during 2013-2014.

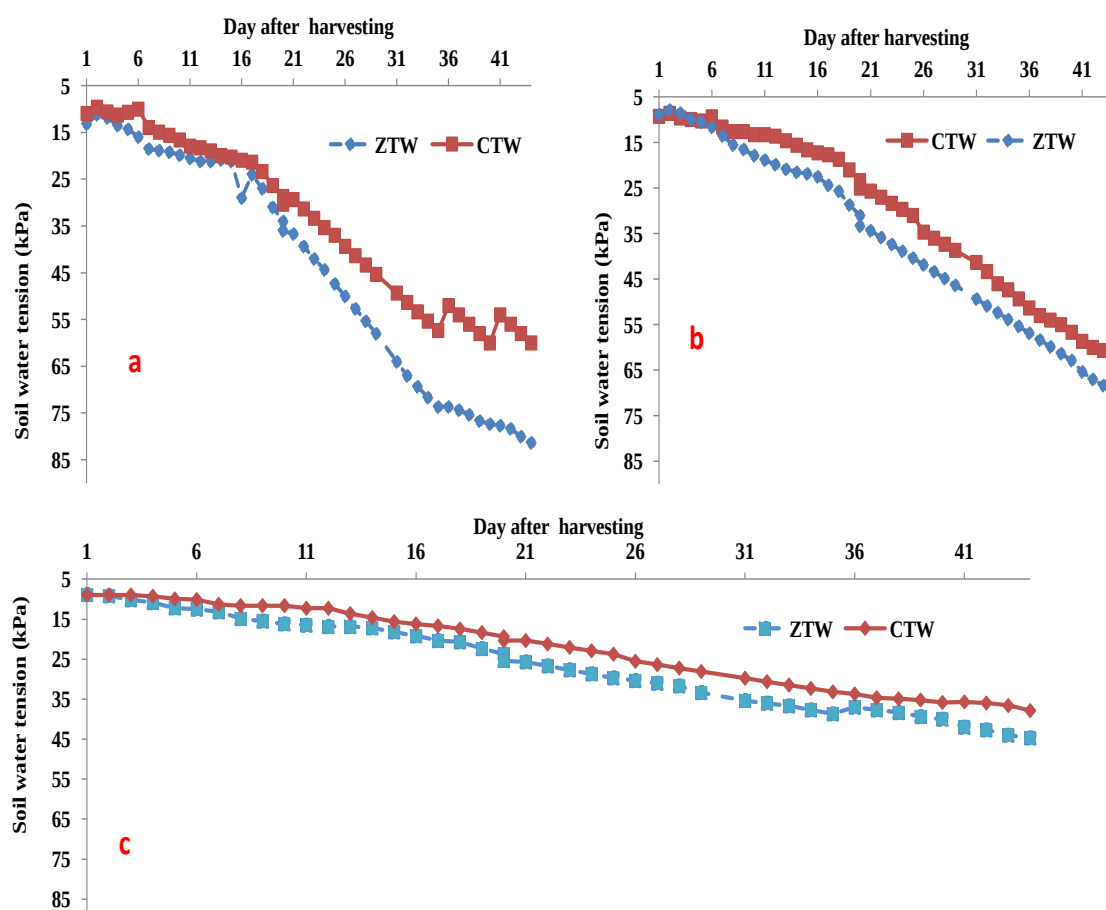


Fig. 9 Soil matrix potential as affected by tillage treatments during the intervening period between wheat and rice at (a) 10 cm , (b) 20 cm and (c) 30 soil depths

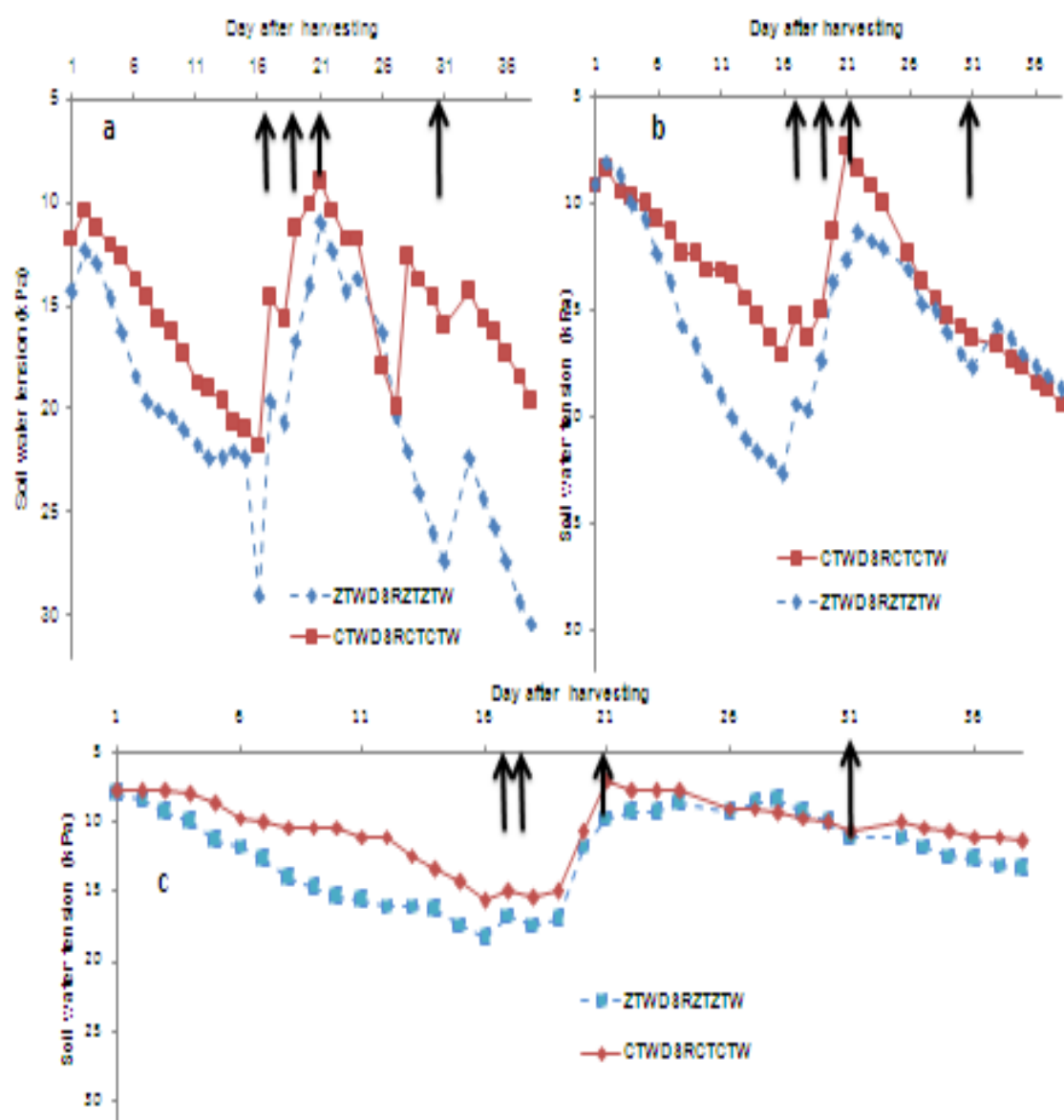


Fig. 10 Soil matrix potential as affected by tillage treatments during the intervening period between wheat and rice at (a) 10 cm , (b) 20 cm and (c) 30 soil depths. (Arrows depicting rainfall events)

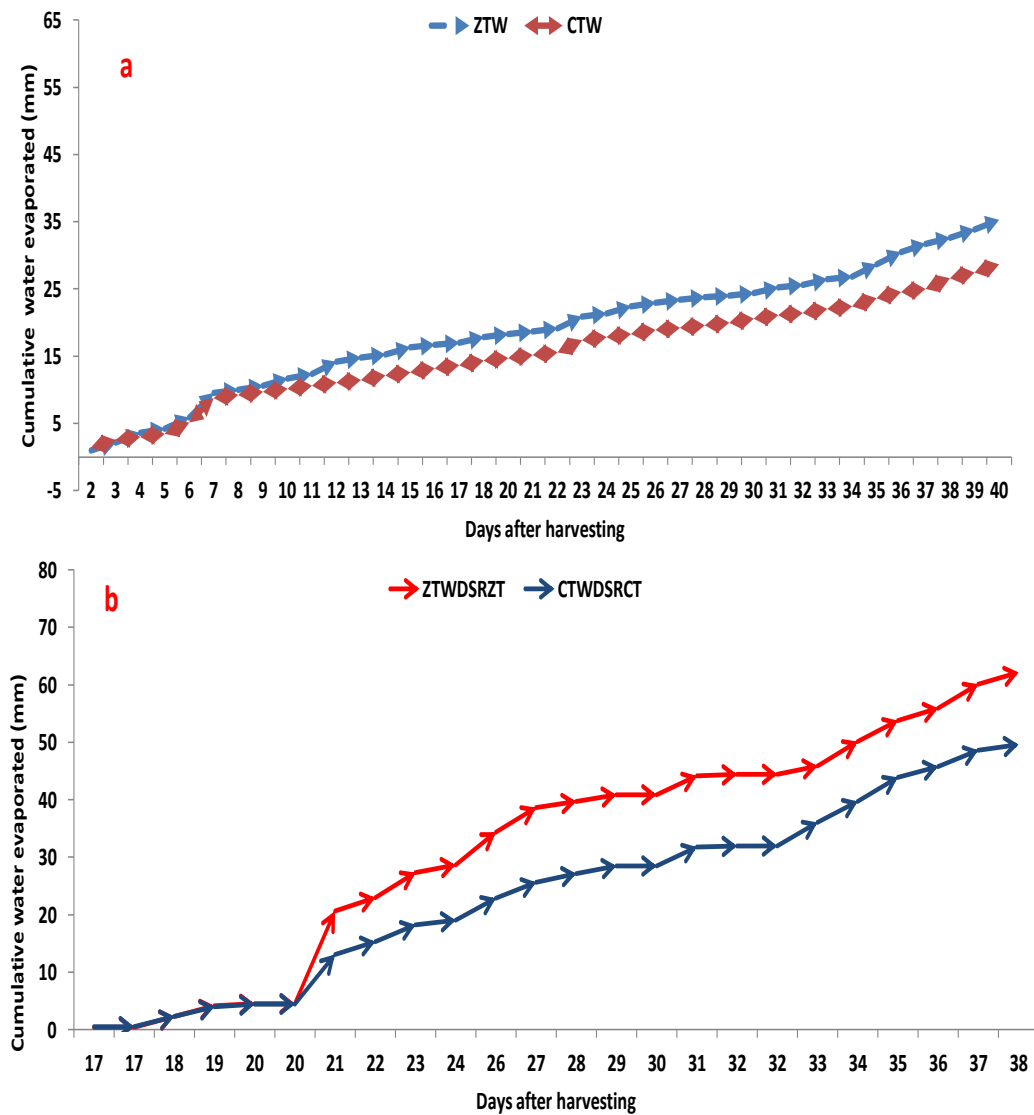


Fig. 11 Cumulative evaporation losses (mm) during intervening period after wheat harvest during (a) 2012-13 and (b) 2013-14

Tillage residual effects on soil moisture dynamics after wheat during intervening period of rice-wheat sequence in South-Asia

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ABSTRACT

An experiment was conducted with an objective was to evaluate the residual tillage treatmental effects viz., conventionally (CT) and zero tilled plots (ZT) on soil moisture dynamics, for which time domain reflectometer (using 7.5 cm and 20 cm probes), tensiometers (at 10, 20 and 30 cm soil depths), soil thermometers (upto 5 cm soil depth) and lysimeters (in selected treatments) were used. The CT plots conserved more moisture than ZT plots (with 2 t ha⁻¹) after wheat. On an average, during the intervening period after wheat, soil matric tension reported to be 28%, 18% and 18 % higher in ZT plots than CT plots in 10, 20 and 30 cm soil depths respectively while soil temperature was 2.2% higher in the ZT plots. Recorded water depths upto 7.5 cm of soil surface was 10.3% higher in CT plots in comparison to the ZT during the intervening periods. Evaporation losses pragmatic to be higher (7.6%) in ZT plots, because of recorded lower mulch loads, higher surface temperature and continuity of soil pores in compare to CT plots and this conserved soil moisture helps in cultivating intervening green manuring crops which further improves the declining soil health, water productivity and finally livelihoods in the region.

Key words: *Intervening moisture retention, Lysimeter, Soil thermometer, Tensiometer, Time domain reflectometer.*

INTRODUCTION

The rice–wheat (RW) cropping systems occupies 13.5 million hectares (m ha) in the Indo-Gangetic Plains (IGP) of India, Bangladesh, Nepal and Pakistan. In India alone, RW rotation occupies about 10.5 m ha and contributes about 40% of the country's total food grain basket. Some establishment methods demanded more irrigation water but they may conserve more water for the intervening crops while other methods may save some water during crop establishment but may demanded higher quantity thereafter.

Soil water retention entirely affected by evaporation (Singh *et al.*, 2014), rainfall received at soil and plant canopy (Hupet and Vanclooster, 2005), plant root water uptake (Garr'e *et al.*, 2011) and root channels (Devitt and Smith, 2002). Godwin (1990) argued that tillage effects on water infiltration dependent on divergent environmental and soil textural classes. Zero tillage (ZT) improved infiltration rate (Nielsen *et al.*, 2005), water retention (Datiri and Lowery, 1991), hydraulic conductivity (Benjamin 1993) which further lessen soil compaction but under the presence of sufficient straw loads as it acts like mulch while the scenario might be entirely different in the absence of the mulch load. Temporal residual soil moisture during the intervening periods is of importance for intervening crops. Number of published studied are there in literature, demonstrating divergent tillage effects on moisture retention during cropping season while till now, very few studies published in this regard during the intervening periods after wheat.

Bhatt and Kukal (2014) after rice reported that in sandy loam

soils, zero tilled plots (with 8.1 percent higher straw load) retained higher soil moisture during intervening period for longer period as compared to conventionally tilled plots. However, studies on this aspect after wheat still lacking in literature important for intervening crops which further improves the soil health and livelihoods. Secondly, moisture retention scenario after rice may follow entirely different pattern than after wheat because of reported higher temperature and longer intervening period of about one month. Keeping this objective in view, this study was planned to study the residual effect of divergent tillage methods viz., conventional and zero tillage on soil matric tension, surface soil temperature, soil evaporation & finally on volumetric moisture retention during the intervening period after wheat.

MATERIALS AND METHODS

A study was planned during the intervening period before rice to monitor temporal variations in moisture retention at the research farm of PAU, Ludhiana during 2013. The soil was sandy loam, non-saline, near neutral with less than 0.5% organic carbon. The climate of the region is subtropical with hot, wet summers & cool, dry winters & the different climatic para-meters during study period shown in Fig.1. During study period three rainfall events were received with a total of 5.6 mm of rain (Fig. 1).

The wheat crop was raised per the recommendations of PAU, Ludhiana with two tillage treatments viz., conventional (CT) and zero (ZT) tillage with three replications. History of experiment site revealed that earlier direct dry seeded rice crop

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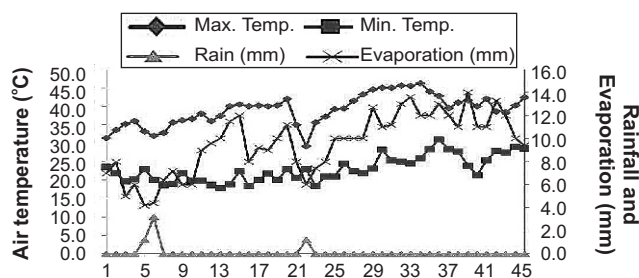


Fig. 1. Different climatic parameters variation during the study period

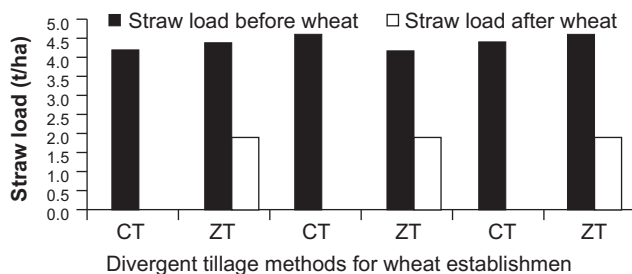


Fig. 2. Straw load in divergently established wheat plots

was established and there was around 4.4 t ha^{-1} of straw load present on the soil surface before the start of experiment. After wheat, this experiment was planned to estimate the temporal moisture retention trends as affected by different tillage treatments by monitoring fluctuating behaviour of soil matric tension, volumetric moisture content and surface soil temperature under differently tilled soils. During implementing treatments in CT plots, which involves disking (thrice), tilling (thrice) and finally planking, all straw loads incorporated into the soil while zero tilled pots involving no tillage retained mulch load (4.4 t ha^{-1}) on it. It was further reported that after wheat season, the straw load present on the ZT plots decomposed to 43% and decreased to 2.0 t ha^{-1} (Fig. 2).

However, different instruments used to fulfil this objective includes.

A). Tensiometers : Soil matric suction variations in differently treated plots help us to understand soil moisture dynamics (Bhatt *et al.*, 2014). Electronic tensiometers depicting soil matric suction variation in a particular plot under a particular treatment (Kukal and Sidhu 2004). Tensiometers were installed at different depths viz., 10, 20 and 30 cm in the soil profile during the intervening period (Fig. 3a). Digital SPEC readings were recorded to understand the fluctuating behaviour of soil matric tension.

B). Mini-lysimeters : Carlos *et al.* (2013) reported that mini-lysimeters were quite effective in understanding fluctuating behaviour of evaporation in divergently tilled plots. PVC pipes which were of 8 inch length and with 4.0 inches diameter were used for preparing lysimeters, filled with the help of chain pulley arrangement, an end cap fixed on one side and then placed inside the outer pipe of bigger diameter which itself was already fixed in the sampled plot (Fig. 3b). Daily mini-lysimeters were weighted using digital balance for measuring grams of water evaporated in a particular tillage treatment.

C). Time domain reflectrometer (TDR) : TDR readings help in understanding temporal fluctuations in volumetric moisture contents in different treated plots (Wraith and Or, 1999). For present study, TDR with 7.5 cm probes was used. Before using, TDR was calibrated by plotting its different readings with the different readings of product of bulk density and gravimetric moisture content in different plots using STAR (Statistical Tool for Agricultural Research) package and r^2 comes out to be 0.77 depicting good relationship in between both plotted parameters (Fig. 4).

D). Soil temperature : Soil temperature particularly of surface soil is quite important in evaporation studies as it causes the phase change of soil water from liquid to vapour phase (Singh *et al.*, 2011). Digital soil thermometers were used for recording daily soil surface temperature in different plots established from upper 2 inch of differently treated plots.

Data recorded from above instruments in differently tilled plots helps in identifying a particular tillage treatment which retained higher sum of volumetric moisture content important for intervening green manuring crops which further improved the soil health, water productivity and finally livelihood of poor farmers.

RESULTS AND DISCUSSION

Soil matric tension (SMT) trends during intervening period : Prepared graphs by daily recorded data (Fig. 3a) of (SMT) readings by soil SPEC depicted that zero tilled dried out faster than conventionally tilled plots after wheat which was mainly because of lesser mulch load (2.2 t ha^{-1}), continuous supply of water from deeper layers due to continuity of soil pores and recorded higher soil temperature throughout intervening period (Fig. 6b) while in CT plots, the continuity of soil pores broken by tillage operations. At 20 cm soil depth, ZT plots dried out quickly while at 30 cm soil depth, both plots dried out at almost similar rate (with increasing magnitude), though ZT plots dried out quickly. At all the soil depths viz., 10, 20 and 30 cm soil depths, SMT values go on increasing. On an average, during the



Fig. 3. Demonstrating different instruments used to monitor soil moisture dynamics

(a) Soil tensiometers installed (b) Capped & filled mini-lysimeter

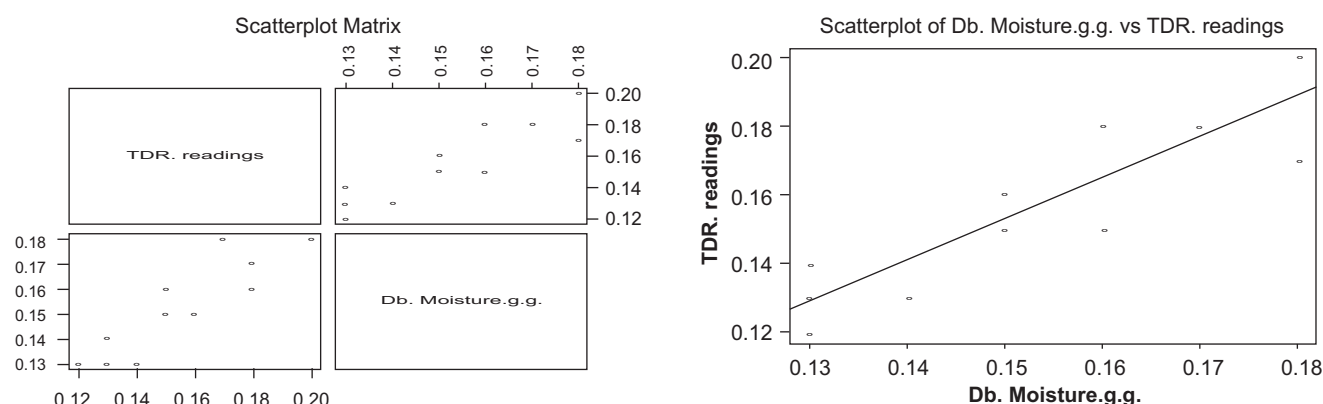


Fig. 4. Calibration of TDR ($r^2 = 0.77$) showed good relation between TDR readings and product of bulk density and gravimetric moisture content

intervening period after wheat, SMT reported to be 28%, 18% and 18 % higher in ZT plots than CT plots in 10, 20 and 30 cm soil depths respectively (Fig. 5 a,b,c). Some rains of lower magnitudes were there but having not effect on SMT. SMT readings in ZT plots increased at much more faster rates than CT plots at all the soil depths indicating greater and prolonged retention of soil moisture in later plots during intervening periods after wheat (Fig. 5) as air temperature started increasing (with an exception to the rainfall day) after wheat harvesting while Bhatt and Kukal (2014) reported higher moisture in ZT plots after rice mainly because of lower temperature.

Volumetric water content variation during intervening period : Time domain reflectrometer (TDR) readings indicate that conventionally tilled plots retained higher quantity of moisture content than zero tilled plots during intervening period. On an average, during the intervening period after wheat, reported water depths in 7.5 cm of soil surface was 10.3 % higher in CT plots in comparison to the ZT during the intervening periods (Fig. 6a) which may be because of recorded lower soil temperature while plots under zero tillage experienced higher soil temperatures (Fig. 6b), leading to faster drying of soil throughout the studied period (Fig. 5).

Variation in soil temperature during intervening period : Basic requirement for evaporation to occur is the energy to cause phase change from liquid water to vapour form. Lesser the energy lesser is the evaporation and lesser the prolonged retained soil moisture while higher soil temperature faster the

evaporation by providing more energy. On an average, during the intervening period after wheat, soil temperature in upper 5 cm of soil surface remained higher (2.2%) in the plots under zero tillage during the study period (Fig. 6b) while in CT plots lower soil temperature recorded in the surface soil responsible for lower evaporation rates which further conserve the moisture for longer periods of time. Further, lower mulch load of 2.2 t ha^{-1} found to be ineffective in conserving the soil moisture in ZT plots, however mulch load of 6.0 t ha^{-1} already found to be effective in conserving the soil moisture (Bhatt and Khera, 2006).

Variation in evaporation during intervening period : Mini-lysimeters were used to study the evaporation trends in differently treated plots during cropping season or during intervening periods. On an average, during the intervening period after wheat, it was (Fig. 6c) clearly depicted that ZT plots evaporate faster (7.6%) than CT plots during the intervening period and already reported higher soil temperature (Fig. 6b) mainly responsible for this. Further, SMT readings jump quickly in the ZT plots than in the CT plots (Fig. 5) depicting quicker drying of soil at different depths in the former plots for which continuity of soil pores mainly responsible while in the CT plots, the continuity of the soil pores disturbed by tillage which restricted continued supply of moisture from the deeper layers to the surface soil.

Zero tilled plots with almost nil straw loads (2.2 t ha^{-1}) were not effective to conserve the soil moisture to a soil depth of 30 cm for a prolonged duration, for to be used by the intervening crops.

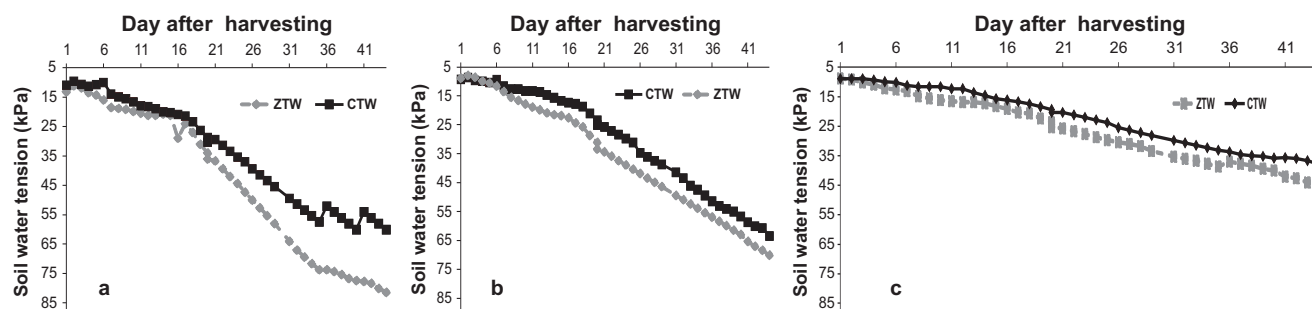


Fig. 5. Soil water tension behaviour as affected by tillage treatments during intervening period at 10 cm (a), 20 cm (b) & 30 cm (c) soil depths

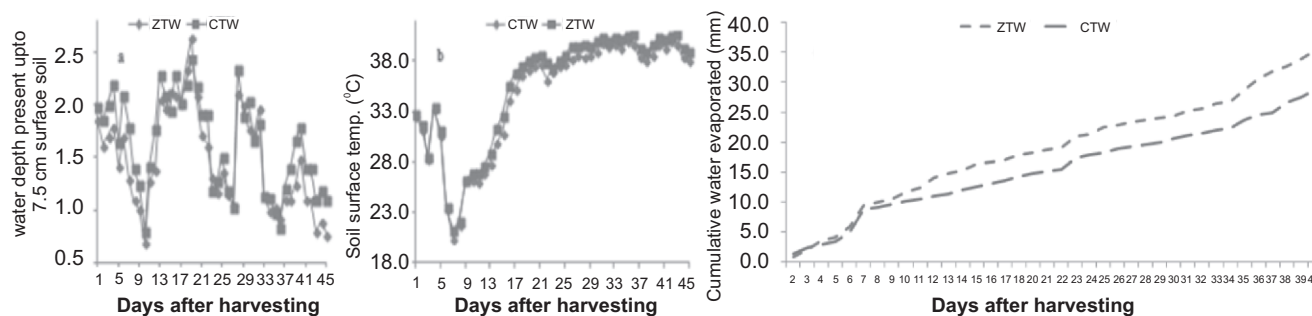


Fig. 6. Water depths present in upper 7.5 cm of soil (a), surface soil temperature at 2.00 pm (b) and mm of water evaporated (c) as affected by residual effect of divergent tillage treatments

Lower straw loads, continuity of soil pores, preserved higher moisture during previous wheat season, higher soil surface temperature during intervening period were some of the recognised culprits for this while in conventionally tilled plots recorded lower temperature, discontinuity of soil pores which were then not able to supply moisture from lower depths were the main factors responsible for conserved higher soil moisture during the intervening period. SMT reported to be 28%, 18% and 18 % higher in ZT plots than CT plots in 10, 20 and 30 cm soil depths respectively while soil temperature was reported to be 2.2% higher in the ZT plots. Recorded water depths upto 7.5 cm of soil surface and evaporation losses reported to be 10.3 % and 15% higher in ZT plots respectively as compared to the CT during the intervening periods.

However, Bhatt and Kukal (2014) reported reverse trends after rice as plots under zero tillage retains higher moisture content than conventionally tilled plots and that was mainly due to reported lower temperatures after rice than after wheat season. Therefore after wheat during intervening periods, conventionally tilled plots retained higher moisture content which might be useful to harvest intervening crop viz., moong and other green manuring crops which further improves the declining soil health, water productivity and livelihoods in the region. Further such studies need to be carried out in texturally divergent soils under different agro-climatic conditions in the region..

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Soil physical environment as affected by double zero tillage in rice-wheat cropping system of North-West India

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ABSTRACT

Highly productive rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) cropping systems are crucial for millions of rural and urban in the Indo-Gangetic Plains (IGP) of south Asia. This intensive RWCS resulted in declining groundwater table and degrading soil health. A number of resource conservation technologies are being propagated in the region to uplift declining water productivity and soil health. Among different propagated resource conservation technologies-double zero tillage (ZT-wheat) in both crops found to be adopted in the region at a large scale which lessens cost of cultivation with no-field preparation and no-pre-sowing irrigation factor. Further, as wheat sown in loose and anchored rice straw thus emit burning of rice residues and finally, reduces air pollution and improves “blank gold” status (Soil organic carbon). Zero tillage supposed to improve the declining soil physical properties; crop and water productivity thought visible effects appeared after 4-5 years of adoption. Our treatment includes two tillage levels viz. conventional and zero tillage and three rice tillage viz. Puddle, conventionally and zero tilled with two establishment methods viz. direct seeded rice (DSR) and mechanically transplanted rice (MTR). Objective of the present study was to delineate the effect of double zero tillage from 2012-2014 on the soil physical environment and our findings suggest that double tillage was not able to significantly effect the physical properties of the soil as adaptation of CA based component technologies evolved over the time. Thus best benefits of double zero tillage might be significant after 3-5 years of continuous adoption of the double zero tillage which further needs to be tested under different agro-climatic conditions under texturally divergent soils.

Key words: Double zero tillage, rice-wheat cropping system, physical environment, North-West India

INTRODUCTION

Rice-wheat cropping system (RWCS) is the most important cropping system for food security in South Asia (13.5 M ha), providing food for more than 400 million people (Ladha et al., 2003) but led to decline of underground soil water and deterioration of the soil health (Hira, 2004; Kukal et al., 2014) in the region. Conventionally, rice is established in puddle soils with heavy water and labor inputs (Dawe, 2005), causes sub-surface compaction because of repeated puddlings of coarse and medium textured soils (Sur et al., 1981; Kukal and Aggarwal, 2003a) restricts the root growth of wheat in addition to creating

aeration stress (Kukal and Aggarwal 2003b). Puddling deteriorated soil physical properties by breaking down soil aggregates, induced changes in pore size distribution; the cone index decreased after puddling and gained strength during the subsidence stage of the puddle soil, and the bulk density of soil increased and hydraulic conductivity decreased 30 and 60 days after puddling.

Generally farmers burnt the paddy residues at their field for timely sowing of wheat seeds during rabi season which cause loss of huge nutrients as about 40% of the N, 30-35% of the P, 80-85% of the K, and 40-50% of the S absorbed by rice remains in the vegetative parts at maturity (Dobermann and Fairhurst 2000) which lost on burning which ultimately detonating the soil physico-chemical health.

To address these challenges of RWCS, conservation agriculture (CA) based alternative tillage and crop establishment methods viz. ZTW-DSRZT have been designed and tested in IGP (Malik *et al* 2014, Jat *et al* 2013). The conservation agriculture (CA) involves a paradigm shift from intensive tillage to zero or reduced tillage, establishment of permanent organic soil cover with economically viable crop rotation that complement reduced tillage and residue retention. Change in the soil physical properties as affected by the double zero tillage (ZTW-DSRZT) had a profound effect on the productivity, profitability and sustainability of the rice-wheat cropping system (Bhaduri and Purakayastha 2014, Dikgwatlhe *et al* 2014). However, the magnitude of benefits of CA based technologies tends to be site and situation specific and cannot be overly generalized across farming systems (Hobbs 2007) and realized after 2–3 years as the adaptation of CA based component technologies evolved over the time (Jat *et al* 2014).

Generally zero tillage adopted only during wheat season but to get the full benefits of ZT, both rice and wheat need to be grown with a ‘double zero-tillage’ system (Jat *et al.*, 2006b; Bhushan *et al.*, 2007). However, few studies present in literature showing the effect of double zero tillage in the RWCS on the physical environment and still doubts are there as within two years some studies showed the significant improvement. Keeping this objective in view, present investigation was made to evaluate the impact of double zero till (ZTW-DSRZT) practised for two years on the different soil physical properties as compared to the conventional methods (CTW-DSRP).

MATERIAL AND METHODS

2.1 Site description

The field experiments were carried out at the research farm (30°54'N, 75°98'E, 247 m above sea level) of Punjab Agricultural University, Ludhiana, India, during 2012-14. The experimental soil was sandy loam (sand 65-68%, clay 11-13%), neutral to slightly alkaline, non-saline and medium in soil organic carbon (0.44%) in the surface layer (Table 1). The soil had sub-surface compact layer (bulk density of 1.74 Mg m⁻³ at 15-30 cm). The available nutrients were in the medium range while moisture content (% g g⁻¹) on an average decreased to 71.5% from field capacity to permanent wilting point. The depth to the ground water at the site was around 24 m and the quality of water was good for all crops (Table 2). The experimental site was under puddle transplanted rice for the last 20 years except that the field was under direct dry-seeded rice (DSR-CT) sown under tilled conditions during the immediate previous year (2012). The climate is subtropical with hot and dry summers (March-June), wet monsoon season (late June to mid-September) and a cool dry winter (October-February). The long-term average annual rainfall is 734 mm, 85% of which occurs during a short period of July-September.

2.2 Treatments and experimental design

The treatments consisted of zero- (direct-drilling of wheat in standing stubbles of the previous crop, ZTW) and conventional-tillage (disked twice followed by 2 passes of tractor-drawn cultivator and one planking, CTW) for wheat in main plots (13.8 m x 25.1 m) with three replications. In the following rice crop, the main plots were split into two subplots for differential rice establishment viz. direct-seeded rice (DSR) and mechanically transplanted rice (MTR). These subplots were further split into three sub-sub plots of 49.7 m² (13.8 m x 3.6 m) for differential tillage treatments in rice viz. puddle (P), dry and (CT) and zero-till (ZT). The tillage treatments in rice were randomly allocated in subplots of both DSR and MTR. During wheat season, rice straw load of 4.4 t ha⁻¹ retained on ZTW plots while during rice season all the straw load was removed. As per objective of present investigation, initial soil physical properties analyzed before onset of the experiment and then after practising double zero till for two years same physical properties analysed again to delineate any significant change.

2.3 Measurement of different physical properties

Bulk density was determined by using the core sampler method (Bodman 1942). In situ bulk density was calculated after obtaining undisturbed soil samples in metallic cores having internal diameter of 5.3cm and depth of 5.0cm from different soil depths (Fig 1d). The fresh weight of soil samples was recorded. The soil fill cores were oven-dried at 105⁰C for 24 hours and were weighted to record dry weight of the samples. The bulk density was then calculated as the ratio of dry weight of soil samples to the internal volume of the metallic core.

The infiltration rate of field was determined using infiltrometer method (Fig. 1a) (Herman 1986) while for the particle size distribution for delineating the textural class of the soil was calculated using international pipette method (Piper 1966) while organic carbon (%) estimated by Walkley and Black's rapid titration method (1934). The moisture content at the field capacity and permanent wilting point in different layers of the soil profile was determined by Pressure plate apparatus (Fig 1b) (Richard and Weaver 1943).



Fig. 1. Measurement of different physical properties of the soil viz. infiltration rate (a), hydraulic properties (b), Hydraulic conductivity and bulk density.

The aggregate size distribution was determined using wet sieving technique (Yoder 1936). To represent aggregation status of soil mean weight diameter was calculated as follow

$$MWD = \frac{\sum_{i=1}^n (d_i W_i)}{\sum_{i=1}^n W_i}$$

where d_i is the mean weight diameter of each size fraction in mm, n is the number of size fractions and W_i is the weight of aggregates in the corresponding size fractions. Saturated (using guleph permeameter) and Unsaturated (using disk permeameter) hydraulic conductivities throughout the soil profile was calculated using the disk permeameter (Fig. 1c).

3. RESULTS AND DISCUSSION

Efforts were made to evaluate the impact of double zero till (ZTW-DSRZT) on the different soil physical properties viz. bulk density, hydraulic conductivity, hydraulic properties (Moisture %w/w at FC and PWP), infiltration and aggregation. Following discussion covers the impact of double zero till technologies on the soil physical environment

3.1 Bulk density ($Mg\ m^{-3}$)

No significant effect of double zero till was observed on the bulk density throughout the soil profile upto 150 cm (Table 1) though surface soil (0-15 cm) showed some increments. However, contrary to our study Jat *et al* (2009) reported that double zero till (ZTDSR-ZTW) had significantly higher bulk density in the 0–5 and 5–10-cm soil profile than with other tillage systems, whereas it was higher under conventional-tillage (PTR-CTW and CTDSR-CTW) in the 10–15 and 15–20-cm soil layers compared with ZTDSR-ZTW. Published studies revealed that puddling induced high bulk density in subsurface layers (15–30 cm) in rice based systems (Sharma and De Datta 1985, Hobbs and Gupta 2000).

3.2 Hydraulic properties (Moisture content %w/w at FC and PWP)

The hydraulic properties throughout the soil profile (upto 150 cm) was not significantly improved as compared to the plots under conventional system (CTW-DSRP) (Table 1) and shorter time period might be one reason for that as the positive effect of conservation technologies realized after 2–3 years as the adaptation of CA based component technologies evolved over the time (Jat *et al* 2014). The moisture content almost reduced to half as the studied scenario shifted from FC to PWP.

169 **Table. 1.** Physical properties as affected by double zero till scenario

Soil Depths	Bulk Density (Mg m ⁻³)		Moisture content (%w/w) at 0.3 bar (FC)		Moisture content (%w/w) at 15 bar (PWP)		Soil texture Sand %, (Clay %)		Organic carbon (%)	
	Initial	ZTW-DSRZT	Initial	ZTW-DSRZT	Initial	ZTW-DSRZT	Initial	ZTW-DSRZT	Initial	ZTW-DSRZT
0-15	1.66	1.68	11.3	11.4	7.7	7.8	64.7, (11.3)	64.8, (11.2)	0.45	0.47
15-30	1.74	1.73	10.4	10.5	6.2	6.1	65.9, (11.3)	66.0, (11.5)	0.42	0.43
30-60	1.59	1.59	12.1	12.1	6.4	6.3	66.8, (12.6)	66.6, (12.7)	0.35	0.36
60-90	1.63	1.62	11.3	11.4	6.7	6.7	67.6, (12.7)	68.0, (12.8)	0.37	0.36
90-120	1.57	1.58	12.1	12.0	7.3	7.4	68.2, (12.3)	68.4, (12.5)	0.34	0.35
120-150	1.61	1.60	12.5	12.6	6.6	6.6	68.8, (11.9)	68.9, (12.0)	0.32	0.32

170

171 3.3 Organic carbon (%)

172 Organic carbon throughout the soil profile remained almost same and was
 173 not significantly affected by the double zero tillage of the wheat rice cropping
 174 system practised for the four seasons (Table 1) which might be because of
 175 retention of straw loads of 4.4 t ha⁻¹ during wheat only. Further, it was observed
 176 that organic carbon decreases down the profile and after 30 cm almost no change
 177 observed in the double zero tilled plots as compared to the conventionally tilled
 178 plots viz. CTW-DSRZT plots

179 3.4 Soil texture

180 Double zero tillage technology in RWCS was not able to influence the soil
 181 texture at all after two years as percent sand and clay remained almost same
 182 through-out the soil profile as it was before conduction of the experiment
 183 indicating that soil texture not influenced by double zero tillage (Table 1)

184 3.5 Infiltration

185 No significant improvement in the infiltration rate and cumulative
 186 infiltration was observed under the double zero till plots as compared to the
 187 conventional system (CTW-DSRP) (Fig. 2 a & b). However, slight improvement
 188 in the cumulative infiltration rate was observed in the double till plots. Jat *et al*
 189 (2009) also reported the similar infiltration rates in double zero till plots than the
 190 plots which were under CTW-PTR.

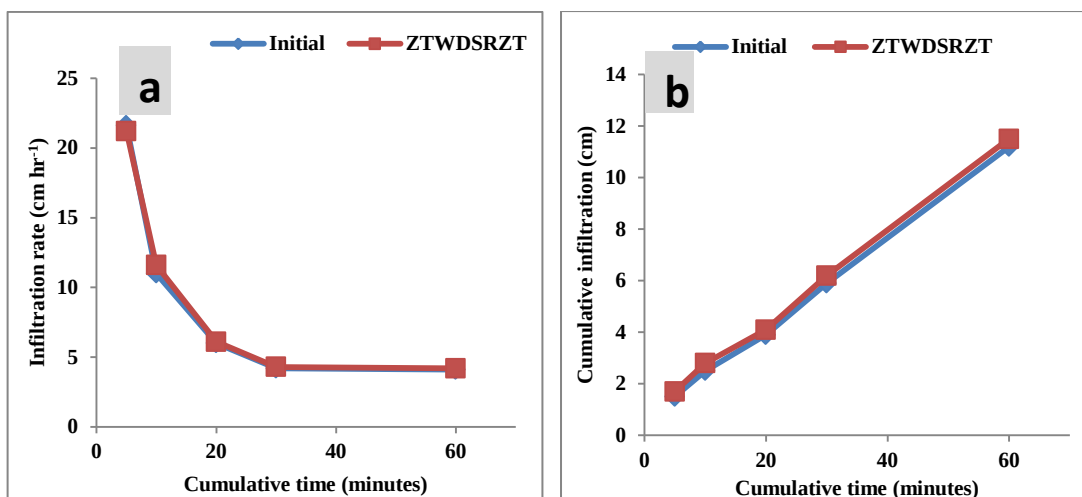


Fig. 2. Effect of double zero till plots on the infiltration rate (a) and cumulative infiltration (b) as compared to the conventional system

3.6 Hydraulic conductivity

Hydraulic conductivities (both saturated and un-saturated) of the sandy loam soil reported to have non-significant effect by the double zero till viz. ZTW-DSRZT during the last four cropping seasons and it's range remain almost similar to that in the conventional system of rice-wheat establishment (Fig 3).

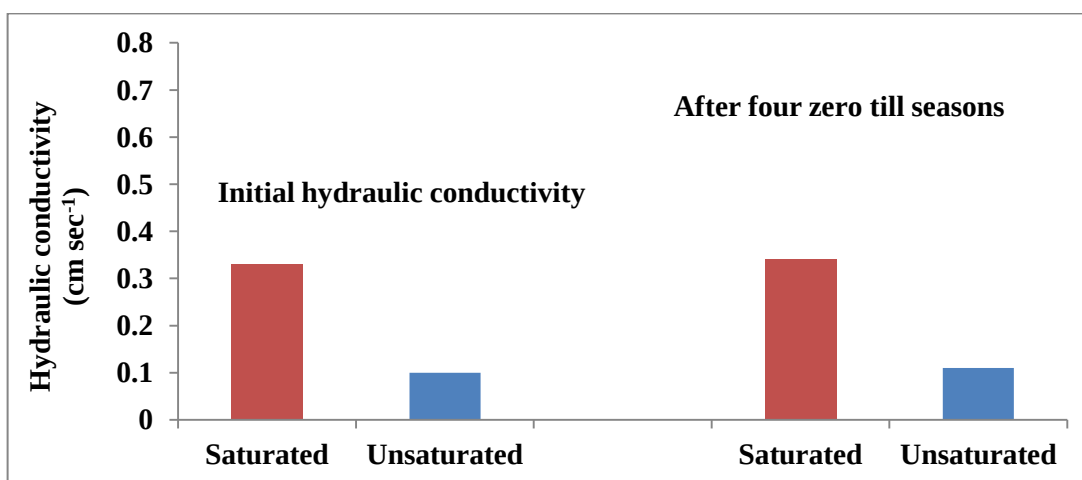


Fig. 3. Saturated and unsaturated hydraulic conductivity as affected by conventional and conservation tillage systems over the last four seasons

3.7 Aggregation/Mean Weight Diameter

The primary soil particles (sand, silt and clay) tend to cohere to form secondary particle called aggregate. The size distribution of aggregates in soils indicates retention of water as their size is important in determining the dimensions of pore space in cultivated soils.

Table 2: Percent soil aggregates initially and doubles ZT plots from last four seasons

Sieve size (mm)	Percent soil aggregates	
	Initial Status	ZTW-DSRZT
>2.0	61.92	61.96
1.0	2.80	2.78
0.5	1.65	1.64
0.25	8.98	8.96
0.10	4.62	4.60
<0.10	20.09	20.06

It was revealed that the mean weight diameter and percentage of weight retained in each size fraction remained almost similar and non-significant effect was observed in plots under conventional tillage and under conservation tillage (ZTW-DSRZT) from the last four seasons (Table 2 & Fig. 4).

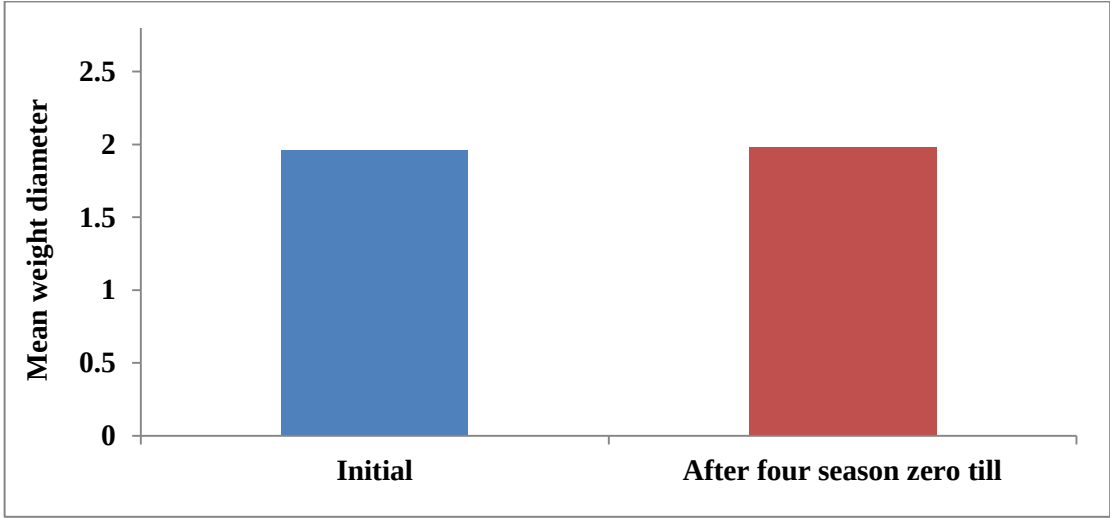


Fig. 4. Mean weight diameter as affected by four season zero till plots

Contrary to result of present study, Jat *et al* (2009) double no-till (ZTDSR-ZTW) had significantly higher soil aggregates (>0.25 mm) than conventional-tillage (PTR-CTW) which might be because of their retained straw load during both the seasons on to the soil surface in double ZT plots while in our study straw load of 44 t ha⁻¹ retained only during the wheat season. Further, under conventional-tillage, soil aggregation was static across the seasons, whereas it improved over time under double no-till and permanent beds. The mean weight diameter of aggregates (average of all size groups) was significantly higher under ZTDSR-ZTW and increased over time compared with conventional-tillage (CTW-PTR).

CONCLUSIONS

Double zero tillage viz. ZTW-DSRZT from wheat 2012-13 to rice 2014 observed to have non-significant effect on the improvement of the different soil physical properties from the initial values. This might be because of the reason that conservation agriculture technologies components including double zero tillage evolved over the time. However after 3-5 years onwards, double zero tillage (ZTW-DSRZT) had a profound improvement in the soil physical environment and thus favourably effect on the productivity, profitability and sustainability of the rice-wheat cropping system. The soil physical properties in terms of soil aggregation, steady-state infiltration rate and compaction does not significantly improved under the double zero-tillage system compared with conventional RWCS. Further evaluation of double zero tillage in RWCS need to be re-evaluated after 5 years and afterwards, double zero tillage may improve the soil physical environment significantly. Further evaluation of double zero tillage viz. ZTW-DSRZT in RWCS is recommended at different agro-climatic conditions under texturally divergent soils for more than 3-5 years to have significant improvement in the soil physical environment.

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Soil moisture dynamics during intervening period in rice-wheat sequence as affected by different tillage methods at Ludhiana, Punjab, India

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Abstract

The objective of this study was to evaluate the residual effect of conventional (CT) and zero tillage (ZT) methods after wheat 2013-14 on moisture dynamics after three consecutive seasons under rice- wheat cropping system at the research farm of Punjab Agricultural University, Ludhiana, India. Soil matric suction (SMT) and water content were measured by using Tensiometer and Time Domain Reflectrometer, respectively at 10, 20 and 30 cm and 7.5 cm soil depths. Soil temperature (by using digital soil thermometer) at 5 cm depth. Evaporation was measured by using Mini-lysimeters. Outcome of study clearly depicted that conventionally tilled wheat plots followed by conventionally tilled direct seeded rice followed by conventionally tilled wheat (CTW-DSRCT-CTW) plots conserved more moisture than the zero tilled wheat followed by zero tilled direct seeded rice followed by zero tilled wheat (ZT-DSRZT-ZTW) plots. On an average, during the intervening period after wheat, SMT was 21, 16 and 17% more in ZT plots than CT plots at 10, 20 and 30 cm soil depths, respectively while soil temperature was 2.1% more in the ZT plots. Recorded water depths upto 7.5 cm of soil surface was 9.5% more in CT plots than ZT treatments. Evaporation losses were higher (12.9%) in ZT plots, due to higher surface temperature and continuity of soil pores. It was concluded from the data that CT treatment retained prolonged and higher contents of soil moisture during intervening period which might be useful for cultivating short intervening crop viz. moong.

Keywords: Intervening soil moisture, time domain reflectrometer, tensiometer, lysimeter, soil thermometer

Introduction

The intensive rice-wheat cultivation in central Punjab, India has resulted in sharp decline in underground water levels during the last few decades (Bhatt and Kukal, 2013). The ground water in north India has been reported to decline by 1 ft year⁻¹, which resulted in the loss of 4 cm raw ground water (Soni, 2012). The environmental pollution on the other hand due to burning of rice residues (to the tune of more than 13 million tonnes every year) has prompted the scientists to find alternate ways of managing natural resources of soil, water and atmosphere. The conservation tillage in the form of direct drilling of wheat in standing rice stubble (zero tillage) is an important resource conservation technology being propagated in the rice-wheat regions of South Asia (Beff *et al.*, 2013; Singh *et al.*, 2014). Zero tillage (ZT) improves the soil physical environment (Bhaduri and Purakayastha, 2014; Paccard *et al.*, 2015) because of the residue retention at the fields resulting in increased infiltration rate, water retention, hydraulic conductivity, lower soil compaction (Bhaduri and Purakayastha, 2014; Palese *et al.*, 2014; Zheng *et al.*, 2015) while conventional tillage breaks macro-aggregates into the micro-aggregates which adversely affect the soil properties

(Roper *et al.*, 2013; Das *et al.*, 2014; Kuotsu *et al.*, 2014) apart from greater losses in soil organic carbon.

The positive benefits of zero tillage (ZT) systems on crop production (Paccard *et al.*, 2015), water use efficiency (Guan *et al.*, 2015), carbon sequestration (Zhangliu *et al.*, 2015) and economic performance (Tripathi *et al.*, 2013) are well recognized. For better irrigation water management, understanding of soil water dynamics during the intervening periods as affected by residual effect of conservation tillage in comparison to conventional system is important (Bhatt and Kukal, 2014 and 2015).

Bhatt and Kukal (2014) reported that after rice, ZT plots (with 8.1% higher straw load) retained higher soil moisture than CT plots during intervening period. They further reported 3.3 and 4.7% higher diurnal soil temperature in zero tilled than that of conventionally tilled plots at 5 and 10 cm soil depths during wheat 2013-14 (Bhatt and Kukal, 2015). The soil water dynamics during the intervening periods may be affected by conservation tillage and needs to be understood for better management of water productivity of the cropping system as a whole. Studies on soil moisture dynamics during the longer

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intervening period after wheat harvest till sowing of rice, as influenced by conservation tillage are not adequately reported in literature. The present study aims to understand the soil moisture dynamics during the intervening period after wheat harvest in a wheat-rice cropping system in a sandy loam soil of Indian Punjab.

Materials and Methods

Field experiments were conducted at the research farm of Punjab Agricultural University, Ludhiana (30°54'N, 75°98'E) and 247 m above sea level during 2012-14 starting from wheat crop. The experimental site was under puddle transplanted rice for the last 20 years except that the field was under direct dry-seeded rice (DSR-CT) sown under tilled conditions during the immediate previous year (2012). The long-term average annual rainfall is 734 mm, 85% of

The tillage treatments in wheat comprised of zero tillage, ZT (direct drilling of wheat in standing rice residues) and conventional tillage, CT (two passes of tractor-driven disk harrow followed by two passes of cultivator and planking) as main plot, rice establishment method viz. direct seeded rice (DSR) and mechanically transplanted rice (MTR) as sub-plot treatments and tillage in rice viz. puddle (PD), dry (DT) and zero (ZT) tillage as sub-sub plot treatments. First wheat crop was established with CT and ZT in 2012 followed by rice in 2013 with two establishment methods viz. DSR and MTR under PD, DT and ZT scenarios followed by wheat in 2013 with similar treatments.

The present study was conducted after wheat 2013-14, to delineate the soil moisture retention dynamics as affected

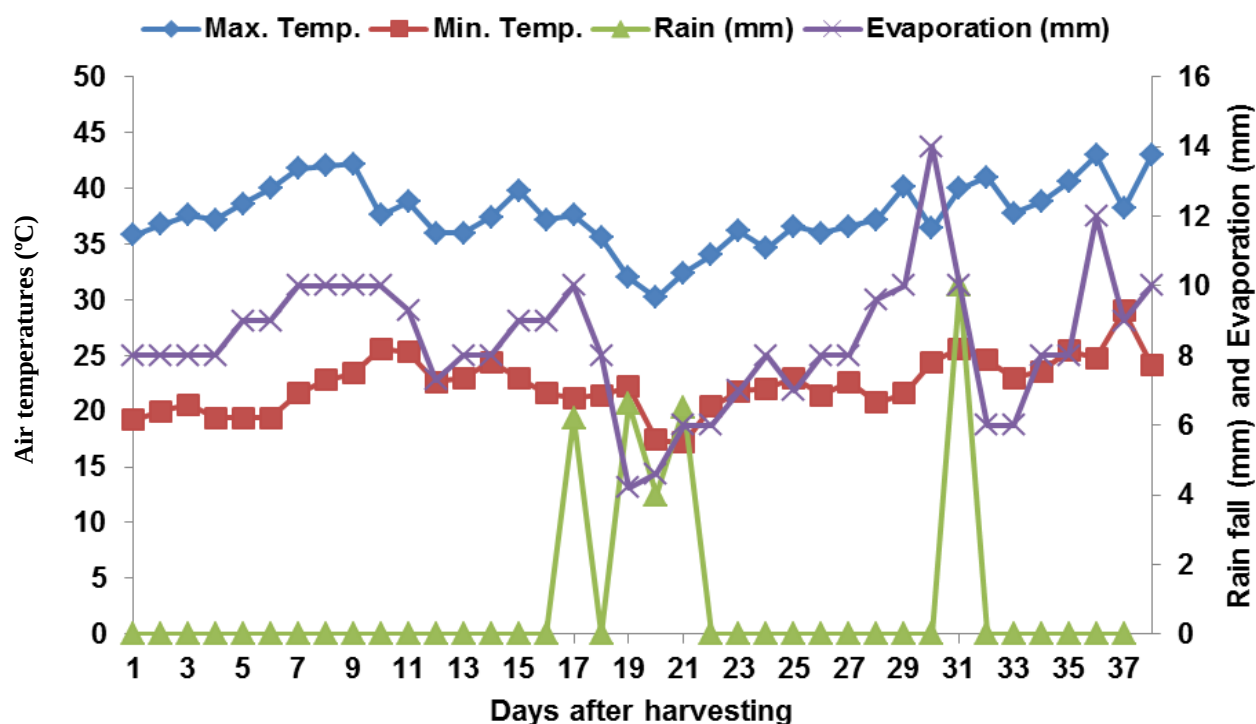


Figure 1: Different climatic parameters variation during the study period

which occurs during a short period of July-September. The studies on intervening period were conducted during the period after wheat harvest till sowing of rice in 2014. The study soil was sandy loam, calcareous, mixed, hyperthermic Typic Ustochrept with subtropical climate. About 26.5 mm rain was recorded during the intervening period under study (Figure 1).

by divergent tillage treatments by monitoring fluctuating behaviour of soil matric tension, volumetric water content, evaporation and surface soil temperature. The soil matric suction was determined by electronic Tensiometer (Kukal *et al.*, 2005; Bhatt *et al.*, 2013). Tensiometers were installed at 10, 20 and 30 cm depths to monitor the soil matric suction in the soil profile during the intervening period



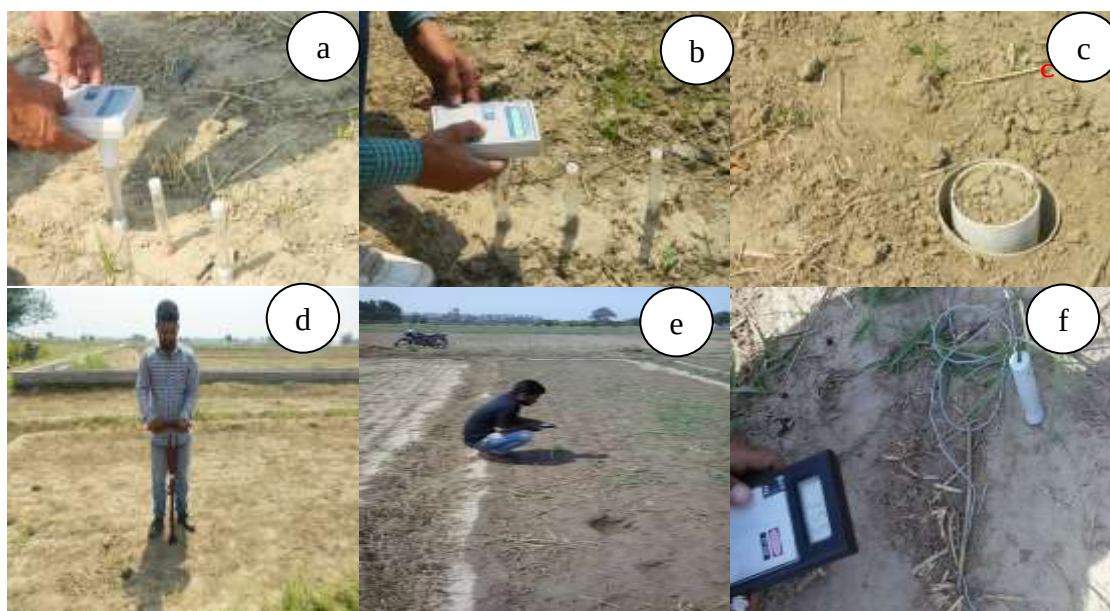


Figure 2: Demonstrating different instruments used to monitor moisture retention under different tillage treatments during intervening period viz. (a) & (b) soil suction with digital soil SPEC (c) capped and filled mini-lysimeter (d) time domain reflectrometer (e & f) measurement of soil temperature using digital soil thermometers

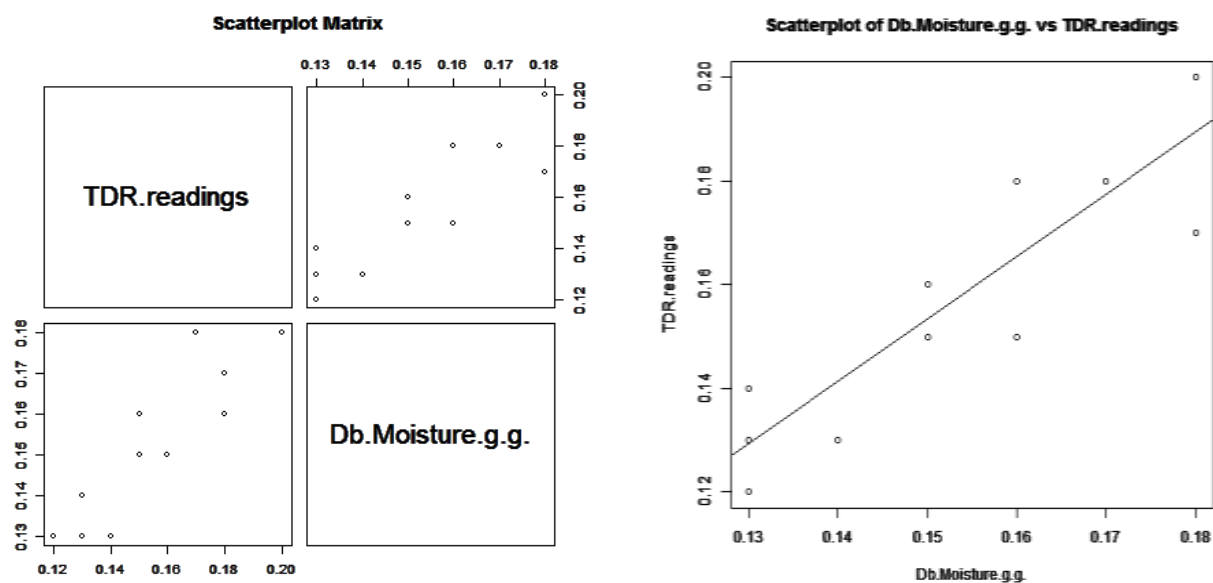


Figure 3: Calibration of Time domain reflectrometer (TDR) ($r^2 = 0.77$) showed good relation between TDR readings and product of bulk density and gravimetric moisture content

(Figure 2). Daily SPEC readings were recorded to understand the fluctuating behaviour of soil matrix tension. The fluctuating behaviour of evaporation under different treatments was determined by using Mini-lysimeters

(Zhang *et al.*, 2009; Carlos *et al.*, 2013). These meters were prepared by using PVC pipes of 8 inch length and with 2.5 inches diameter. Mini-lysimeters were filled from a particular treatment with the help of chain pulley arrange-



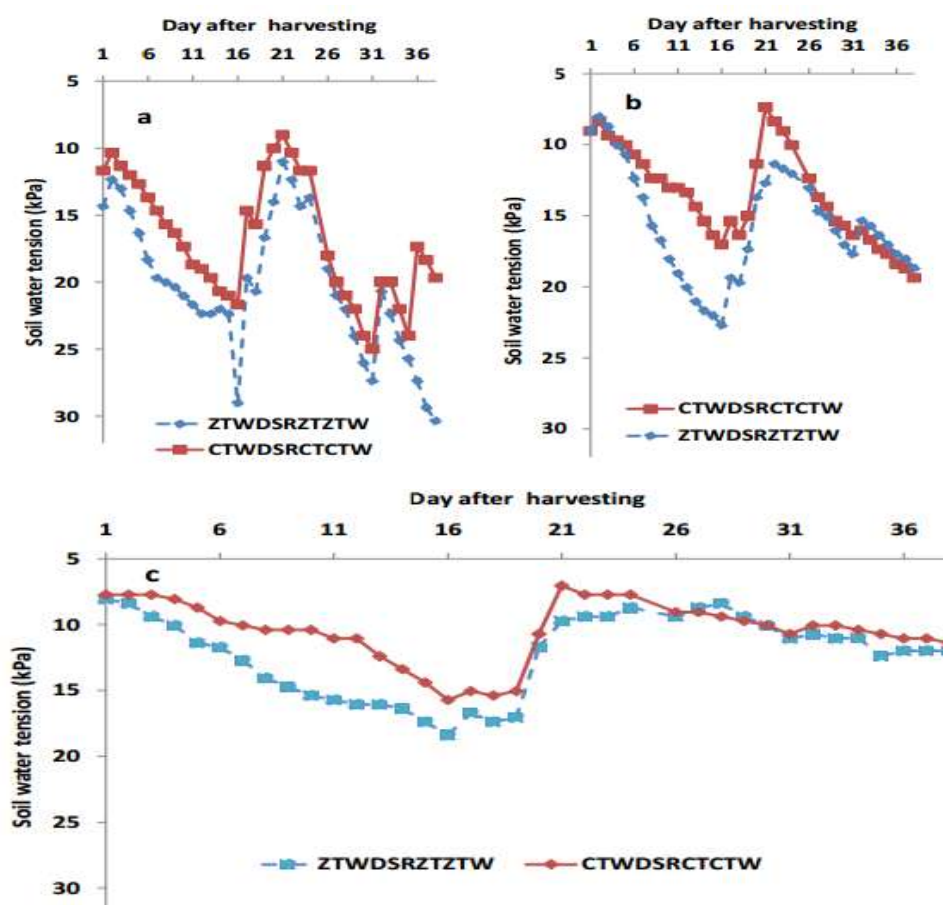


Figure 4: Soil water tension behaviour in relation to different establishment methods at 10 cm (a), 20 cm (b) and 30 cm (c) soil depths. (Arrows depicting rainfall events) (ZTWDSRZTZW=Zero tilled wheat followed by zero tilled direct seeded rice followed by zero tillage wheat, CTWDSRCTCTW = Conventionally tilled wheat followed by conventionally tilled direct seeded rice followed by conventional tilled wheat)

ment, an end cap fixed on one side and then finally filled and capped mini-lysimeter was placed inside the outer pipe of bigger diameter which was already fixed in the sampled plot (Figure 2). Daily mini-lysimeters were weighted at field using digital balance to have an idea of evaporation. The temporal fluctuations in water contents in plots established under different establishment methods were monitored by using Time Domain Reflectrometer (TDR) (Hallikainen *et al.*, 1985; Wraith and Or, 1999). TDR with 7.5 cm probes was used (Figure 2). Before using, TDR was calibrated by plotting its different readings with the different readings of product of bulk density and gravimetric water content in different plots using STAR (Statistical Tool for Agricultural Research) package and r^2 comes out to be 0.77 depicting good relationship in between both plotted parameters (Figure 3).

Soil temperature was measured by using digital soil thermometer (Figure 2). Daily fluctuating readings of soil matric tension, soil temperature, soil evaporation helps us to identify an integrated package of tillage treatment (Figure 3) which could conserve higher soil moisture by maintaining evaporation losses during intervening period and this conserved moisture helps to cultivate intervening crops.

Results and Discussion

Soil matric suction trends

At 10 cm soil depth under ZT dried out much more quickly than the plots under CT which was because continuity of soil pores and recorded higher soil temperature and retained higher moisture during wheat season (Figure 4) while in CT plots, the continuity of soil



pores was broken by tillage operations. At 20 cm soil depth, ZT plots dried out quickly while at 30 cm soil depth, both the plots receiving differential tillage treatments dried out at almost same rate though ZT plots dried out quickly. On an average, during the intervening period after wheat, SMT was 21, 16 and 17% more in ZT plots than CT plots at 10, 20 and 30 cm, respectively. In general, at all the soil depths

moisture as compared to the plots under ZT during the intervening periods after wheat as air temperature started increasing (with an exception to the rainfall day) after wheat harvesting (Figure 5).

Volumetric water content

Conventionally tilled wheat (CTW) plots had higher

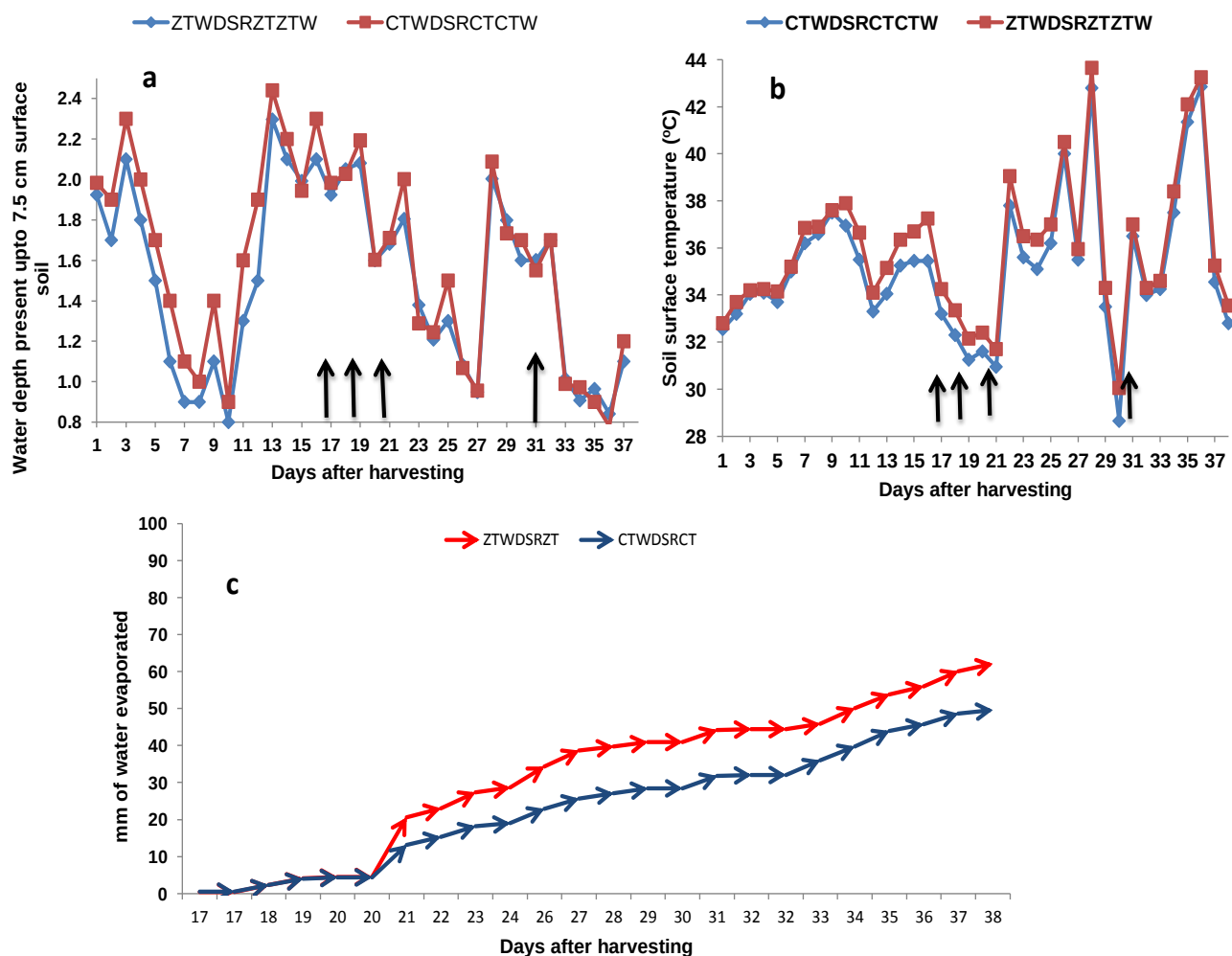


Figure 5: Variation in volumetric water content (a), surface soil temperature at 2.00 pm (b) and cumulative water evaporated, mm (c) as affected by residual effect of different tillage treatments (Arrows depicting rainfall events) (ZTWDSRZTZW=Zero tilled wheat followed by zero tilled direct seeded rice followed by zero tillage wheat, CTWDSRCTCTW=Conventionally tilled wheat followed by conventionally tilled direct seeded rice followed by conventional tilled wheat)

SMT values go on increasing at 16 days after harvesting (DAH) while on 17 DAH, the SMT values decreased due to rainfall. Generally SMT in ZT plots increased at much more faster rates than the plots under CT plots at all the soil depths indicating greater and prolonged retention of soil

moisture content than the ZTW plots. Recorded water depths at 7.5 cm of soil surface was 9.5% higher in CT plots which may be because of recorded lower soil temperature in CT plots while plots under zero tillage experienced higher soil temperatures (Figure 5b), leading to



faster drying of soil throughout the intervening period (Figure 4).

Soil temperature

Soil temperature affects the absorption, translocation of water and nutrients in soil and plants (Moraru and Rusu, 2012). Higher the soil temperature faster the evaporation and lesser the soil moisture retention. On an average, soil temperature was 2.1% higher in the ZT plots during the study period (Figure 5b) while in CT plots lower soil temperature was recorded in the surface soil responsible for lower evaporation rates which further conserved the moisture for longer periods of time.

Evaporation

It was revealed that evaporation trend observed to follow $ZTW-ZTDSR-ZTW > CTW-CTDSR-CTW > ZTW-CTDSR-ZTW$ (Figure 5c). The triple ZT plots were reported to have higher evaporation losses (12.8%) as compared to the triple CT plots during intervening periods. The zero tilled plots (without straw load) having higher soil temperature, soil matric tension values resulted in higher evaporation losses during intervening periods after wheat. It was mainly because of the continuity of the soil pores and recorded higher soil temperature however in the CT plots, continued supply of moisture from the deeper layers to the surface soil prohibited as regularity of the soil pores was disturbed by tillage operations during field preparations. Moreover, the soil temperature was also recorded to be on the lower side in the CT plots as compared to the ZT plots which further promoted higher evaporation losses in the ZT plots

Conclusion

The study leads us to conclude that CTW plots retain higher soil moisture content than ZT plots during the intervening period after wheat harvesting till rice sowing in sandy loam soils. However, there is a need to carry out such studies in texturally divergent soils under different agro-climatic regions to understand the intervening soil moisture dynamics as affected by residual effects of different resource conservation techniques in the region.

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