SOIL PROPERTIES AND NUTRIENT UPTAKE BY RICE UNDER DIFFERENT FERTIGATION REGIMES IN RICE BASED CROPPING SYSTEMS

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2017

Dedicated to my
Maa-Baba
and my family

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It is further certified that such help or information received during the course of this investigation and preparation of the thesis have been fully acknowledged.

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Abstract

Nutrient and water management are important for diversifying and intensifying the rainfed rice based cropping systems. A fertigation experiment in split plot design was laid out at the farm of BAC, Sabour in 2014 with three levels of fertigation in main plots (nitrogen levels as fertigation @ 20, 40, and 60 kg ha^{-1} in rice and irrigation levels @ 200, 300 and 400 mm in post rice crops) and four rice based cropping systems as sub plot treatments (rice followed by either durum wheat, barley, lentil or chickpea). The third year rice crop in the system was used for taking observations on growth and yield, soil physical and chemical parameters and nutrient uptake in terms of N, P and K using standard methods. Fertigation levels and cropping systems can be significant determinants of crop yields. They also have distinct influences on soil conditions and nutrient relations. Most of the significant influences are cyclic, being observable only during a part of the year. Rice grain yield was significantly greater under higher fertigation regimes. Steady state infiltration rate was found higher under rice-legume cropping systems in comparison to any of the rice-cereal cropping systems (i.e. rice-durum wheat and rice-barley) but no influences of fertigation and cropping systems on bulk density were observable. Fertigation regimes and cropping systems can influence the profile penetration resistance.

Maximum water holding capacity of surface soil after the harvest of *rabi* season crops was significantly greater under the higher fertigation regimes. Soil organic carbon was reduced in rice legume cropping systems, likely because of greater rate of organic matter decomposition under higher nitrogen fixation as well as due to the effect of heterotrophic *Rhizobia* colonising the legume roots. Nitrogen availability at the start of the rice growing season *aka.* left over available nitrogen by the *rabi* season crops in the sub-soil layers was significantly greater in treatments receiving less irrigation during the *rabi* season. Cropping systems influenced the availability of nitrogen in the soil after rice harvest as a result of differential nitrogen applications and contributions of the preceding crops and followed the trend rice-chickpea < rice - durum wheat < rice-barley = rice-lentil cropping systems. The available nitrogen content in the 15-30 cm and 30-45 cm soil layer was also significantly lower in rice-chickpea cropping system in comparison to other cropping systems.

Before rice crop establishment, the average P availability in the surface soil and at the depth of 15-30 cm in the soil followed the trend rice-lentil > rice-chickpea > rice-durum wheat = rice-barley cropping systems. At the depth of 30-45 cm, rice barley cropping system exhibited statistically lower availability of P in comparison to other cropping systems. This

again shows the probable effect of heterotrophic *Rhizobia*, which act as phosphate solubilizers while consuming soil available nitrogen in decomposing organic matter. Available K was found to be statistically similar across various fertigation regimes and cropping systems.

N fertigation @ 60 kg ha^{-1} and 40 kg ha^{-1} demonstrated significantly greater nitrogen uptake by rice grains in comparison to 20 kg ha^{-1}, which is due to significantly greater rice grain yield under these treatments. P content in rice straw was found to be lower with 40 kg ha^{-1} and 60 kg ha^{-1} N fertigation compared to 20 kg ha^{-1} N fertigation because of the dilution effect under greater N application. P uptake by rice grains was significantly greater in rice-lentil and rice-durum wheat cropping systems in comparison to rice-chickpea and rice-barley cropping systems which probably is the result varying rates of P addition and extraction resulting in greater P availability in certain treatments at the start of the season.

K content in rice straw was found to be significantly more in rice- durum wheat cropping system compared to rest three cropping systems. This resulted in low K availability after harvesting of rice in rice -durum wheat cropping system than other cropping systems. K content in rice straw was greater in rice-durum wheat cropping system because of greater application of potassic fertilizer (MOP) cumulated over both *rabi* and *kharif* seasons. A significant effect of cropping systems on the internal nutrient use efficiency of P was observed as rice-barley cropping system had significantly greater internal phosphorus use efficiency than the other three cropping systems. The partial factor productivity of applied nutrients was significantly affected by fertigation regimes in case of N, P and K as N fertigation had a negative relation with the partial factor productivity of applied nitrogen but a positive relationship with the partial factor productivity of applied P and K. The phosphorus harvest index was significantly greater when N fertigation was given @ 40 kg ha^{-1} in comparison to when N fertigation rates were 20 and 60 kg ha^{-1}. Phosphorus harvest index was significantly lower for rice-durum wheat and significantly greater for rice-lentil cropping system in comparison to other systems. The physiological phosphorus and potassium use efficiencies of rice were significantly higher under higher levels of N fertigation.

An analysis of the salient findings and reasoning based on pre-existing literature lead us to the conclusion that fertigation and cropping systems do have significant influences on productivity of rice based cropping systems along with soil physical conditions and nutrient relations in soils and plants. These influences might have resulted from the interactive effects of diverse microbial communities acting under the differential nutrient additions and removals as well as soil profile moisture conditions influencing the root growth, exudation, and decomposition created by the imposed treatments. Most of the influences are not long lasting but their ephemeral nature can be an indicator of the direction of changes expected in the long term. Hence, the decision of fertigation in rainfed rice based ecologies should not only take into consideration the objectives of efficient water and nutrient delivery but also the ecosystem characteristics on a cropping systems basis.

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Introduction

Chapter-1

INTRODUCTION

Rice is the most important cereal crop in Asia and it is the main source of protein (15%) and energy (21%) for the population (Depar *et al*., 2011). It is cultivated in a wide range of environments, from tropical to temperate and from aerobic soils in uplands to wet lowlands with uncontrolled flooding (Lal *et al*., 2016). Ismail *et al*., (2012) reported that irrigated lowland rice systems comprise about 55 per cent of the total rice area worldwide and contribute to 70 per cent of the global rice production, while rainfed lowlands and flood-prone areas constitute about 35% of the total rice area, but contribute only 25% of global rice production because of uncontrolled hydrology and various biotic and abiotic stress factors associated with rainfed ecosystems. According to Zeigler *et al*. (1995), over 90 per cent of this rainfed lowland area is located in South and South-east Asia, and these rainfed lowland agro-ecosystems are characterized by a high degree of variability in soil conditions and uncertainty of water supply, which are unfavourable for rice production. They are also generally operated by small-scale farmers with limited access to capital. Rice crop performance is thus very low compared to intensive irrigated systems (Zeigler *et al*., 1995) and yields vary from year to year and from location to location (Boling *et al*., 2010). In India the rainfed rice area covers 12.9 m ha in eastern states including Odisha, West Bengal, Jharkhand, Assam, Chhattisgarh and Bihar. These areas are characterized by soils that are relatively heavier in texture, have better moisture holding capacity to support a good second crop and, are kept fallow after rice in most of the areas (Lal *et al*., 2017). Rice yields on an average range from 1.0–2.4 t/ha in the rainfed lowlands, which occupy 48 per cent of the total rice lands (Tomar, 2002).

In rainfed low land areas of several districts of south Bihar, farmers grow a rainfed rice crop and are usually inclined to leave their land fallow during the *rabi*

season because of the unavailability of ample soil moisture. Soil moisture availability is the main limiting factor in this area for growing a dry season crop following a rainfed rice crop. These areas receive abundant rainfall during the four southwest monsoon season months (June-September), but most of it is not easily accessed and put into beneficial use before it evaporates or flows into sinks and goes off as runoff. Uneven distribution of rainfall coupled with lack of irrigation, results in the rainfed areas becoming mono-cropped with low cropping intensity and farm productivity. Such a situation can be overcome if the farmers are able to grow *rabi* season crops just after the harvesting of rainfed rice for making optimum use of the residual soil moisture. Water deficit, however, is not the only factor limiting crop production in the rainfed lowlands. Poor soil fertility along with less fertilizer use than recommended in the field, and low fertiliser use efficiency resulting from improper timing and method of fertilizer application contribute to a large gap between attainable yields and current yields of farmers. There is a scope for large scale adoption of direct seeded rice in flood affected and rainfed low land areas, with significant reduction of production costs and water use in *rabi* season and subsequent increase in farmers' income (Lal *et al.,* 2016).

The rotation of rice with barley provides typical moisture and nutrient extraction pattern from deeper soil layers due to its long root length. Besides, when rice is cultivated with biologically nitrogen-fixing leguminous crops then it is possible to supply nitrogen and reduce dependence on nitrogenous fertilizer (Ladha and Peoples, 1995). Legumes are also known to be effective in increasing and conserving mineralized soil nitrogen for subsequent use of rice (Buresh *et al.,* 1989; Singh *et al*., 1999). The effects of legumes observed by Sharma *et al.* (2005) were attributed to below ground processes and leaf fall because above ground residues were removed at harvest. Root and stem nodules of legumes can contain significant amount of N

varying from 13 to 50 kg/ha (Ladha *et al.,* 1996). Introduction of legumes can provide a sustainable production base to the continued rice mono-cropped system, which is otherwise leading to decline in total factor productivity (Lal *et al*., 2017). Inclusion of legumes in the rainfed rice system can help in maintaining a less negative balance of nitrogen, the post rice-chickpea increased the soil nitrate plus ammonium N before rice more than the post rice fallow system, so rice grain yield and N accumulation following chickpea were higher by almost 1.0 t/ha and 20 kgN/ha respectively, than that of rice after fallow under direct seeded conditions without N fertilizer application (Patil *et al*., 2001). Oilseed crops with their tap roots and deeper root system have the capacity of extracting subsoil water from greater depths (Kar *et al*., 2006). There are numerous published papers describing how penetrometer resistance depends on ephemeral soil properties such as water content, density and matric potential (Whalley *et al*., 2007; Vaz *et al*., 2011). Soil factors influencing penetration resistance are matric potential (or water content), bulk density, soil compressibility, soil strength parameters, soil structure and others (Bradford, 1986). Many studies have been conducted to understand the influence of bulk density and water content on penetration resistance in the laboratory (Taylor and Gardner, 1963; Ohu *et al.*, 1988) and field (Vazquez *et al*., 1991; Busscher *et al*., 1997).

Traditionally, the farmers in south Bihar, cultivate *rabi* season oilseeds such as linseed and pulses such as lathyrus, chickpea and lentil and usually go for rice crop establishment as puddled transplanted rice. In some regions of eastern India, farmers grow lentil as second crop by broadcasting the seeds within the standing rice crop in well-moistened soils without any tillage 15–20 days prior to the harvest of rice (relay cropping) and obtain much less yield from lentil (Bandyopadhyay *et al*., 2016). It might be due to unfavourable physical conditions of the soil which inhibit crop growth and nutrient uptake in rice-fallow (Layek *et al*., 2014). This crop, however, contributes

substantially to enriching soil fertility of these soils by enhancing microbial activity, fixing atmospheric nitrogen and adding organic matter (Gangwar *et al*., 2006), and at the same time enables the farmers to get some economic yield from the second crop which could not have been possible with any further delay in sowing. A previous study in eastern India revealed no positive effect of a post-rice chickpea crop on subsequent transplanted rice (Singh *et al*., 1999), whereas a subsequent study showed higher yield of direct-seeded rice when following chickpea rather than a traditional fallow (Patil *et al*., 2001). One contributing factor to the advantage of direct-seeded rice is an earlier date of maturity, which increases the chance of escaping terminal drought that often occurs in rainfed lowlands of eastern India (Sastri and Singh, 2000). The earlier maturity of direct seeded rice could also contribute to earlier establishment and hence greater productivity of the post-rice food legume and therefore, increase opportunities for system intensification and diversification (Mazid *et al*., 2002).

Early crop establishment in aerobic soils, such as by direct seeding, favors higher root and shoot growth, which enables water extraction from a larger soil volume and deeper layers compared with transplanted rice (Naklang *et al*., 1996; Bridgit and Potty, 2002). According to Bridgit and Potty (2002), under drought conditions, direct dry-seeded rice experiences less water stress and yields significantly higher than transplanted rice. Singh *et al.* (1995) showed that direct-seeded rice had more uniform water extraction pattern from various soil depths, and withstood drought for a longer period than the transplanted crops. Fertigation and profile root water extraction by respective crops, could comprise the major components of the water budget of the rainfed ecology under study. Hence the two are likely to be the major factors affecting the wetting and drying cycles of the soil; the other two likely ones being precipitation and evaporation. Thus fertigation as well as soil water extraction by the roots through supplemental irrigation can potentially influence the wetting-drying cycle, and thus

result in variable penetrability of roots in the profile and influence water use efficiency in rice based cropping systems. Other crops such as barley and durum wheat, which have a lower water requirement, can also be suitable for the system. These crops, though traditionally grown under rainfed situations, can respond to irrigation at critical junctures. If some supplemental irrigation can be made available for the *rabi* season crops, efficient water and nutrient delivery systems such as fertigation in rainfed rice based systems can be explored. Fertigation provides efficient use of soil nutrients and moisture to the crops and reduces the risk of low crop productivity. Water efficient crop establishment methods in rice based systems with fertigation can be explored for tackling the issues of low productivity and nutrient availability. These practices may be effective in improving soil physical conditions as well as sustaining soil fertility. Differential fertigation regimes can potentially alter the soil profile moisture regime, fertility, water use efficiency, and may also improve the soil profile physical conditions. Similarly, various rice based cropping systems that involve various cereals, pulses or oilseeds in rice based system, may also result in varying soil moisture regimes, fertility, water use efficiency and soil physical conditions. This is expected because of the different rooting, and the resulting differential extraction of water and nutrients from the profile. Moreover, soil physical constraints such as compaction, low water holding capacity, infiltration rate and high penetration resistance of soil to roots can adversely affect plant growth in rainfed areas. So, optimizing water and nutrient management, crop rotation and overall management system is necessary for increasing the productivity and intensity. An adjusted irrigation regime may help to minimize the risk of soil compaction, which is a major yield constraining factor in global crop production, constituting a serious issue in the rice based cropping systems of the eastern India plain. Thus this study aims to evaluate the resulting changes in soil conditions in terms of water holding capacity, soil penetration resistance (PR), soil

bulk density (BD) and soil fertility attributes resulting from wetting / drying (WD) cycles of various fertigation regimes under different rice based cropping systems. These were tested under various fertigation levels (Nitrogen levels applied through fertigation during *kharif* and irrigation levels during *rabi*) over various rice based cropping systems imposed in an experiment from June 2014. The present investigation evaluates their effects before and after the third rice crop in the system. Various crop management practices that use soil nutrients efficiently with moderate amounts of nutrient inputs while simultaneously reducing risk are essential for stabilizing and increasing rice yields in rainfed lowlands (Pandey, 1998).

Supplemental irrigation had a beneficial effect on crop grain yield of winter and dry season crops (Kar *et al*., 2006). The soils in these lands are fully saturated during the rice growing season. The residual moisture left in the soils at the time of harvest is sufficient to raise short-season legume and oilseed crops, such as groundnut, lentil, rapeseed and mustard (Musa *et al*., 1998; Bourai *et al*., 2002). Efficient resource management using leftover soil moisture and nutrients after the preceding rice crop can convert lowland rice farming into a profitable enterprise (Musa *et al*., 1998; Maclean *et al*., 2002). Different rice based cropping systems as well as the effects of fertigation regimes may modify the root penetrability and hence the nutrient extraction by roots from various depths of the soil profile. Hence we hypothesize that

- Soil physical properties are a function of cropping systems, fertilizer application and irrigation.
- Nutrient extraction from different layers of the profile by crops is a function of the cropping systems, fertilizer application, irrigation and soil physical conditions.

The fertilizer application through fertigation which results in different water regimes in different soil layers at various times can provide an opportunity

for a more effective use of land, nutrients and moisture to improve productivity, reduce risk in rainfed lowlands in south Bihar and increase cropping intensity of rainfed rice based cropping systems. Hypothetically, this can be achieved by efficient nutrient application during the rainy season and enabling the growing of a second crop during dry winter season using supplemental irrigation from harvested rainwater. Hence studies with the following specific objectives have been proposed to test the above hypotheses:

1) To assess the effect of fertigation levels and rice based cropping systems on soil characteristics.
2) To evaluate the effect of fertigation levels and rice based cropping systems on nutrient uptake by rice crop.

Review of Literature

Chapter- 2

REVIEW OF LITERATURE

2.1 Introduction

Lower soil moisture availability is the main factor limiting the growing of a post rice crop in rainfed rice fallows of eastern India. Rainfed rice is grown with traditional practices during the rainy season (June- October) with large areas (13 m ha) remaining fallow during the rainy season (November-March) inspite of annual rainfall of the order of 1000-2000 mm (Kar *et al.*, 2006). In rainfed lowland rice ecosystems, water stress, uneven distribution of rains and significant gaps between rains, with low soil organic matter and low fertilizer application rates are commonly the most severe limitations to productivity of rice (Widawsky and O'Toole, 1990), and grain yields average 1.0, 2.3 and 1.6 t/ha under upland, rainfed lowland and flood-prone conditions, respectively (IRRI, 1993).

Diversified crop rotations with rice crop variously influence soil properties due to addition of different levels of crop residues and root exudates that are incorporated in the soil, more so because the residues and the exudates have different chemical composition that affect the soils differently. This has effects on soil organic matter decomposition, water holding capacity, enhancing plant nutrient transformation and availability. Crop rotations play an important role in nutrient recycling because plant species vary in their abilities to produce biomass, efficiency to absorb ions, and they extract nutrients from different soil depths (Mengel and Kirkby, 1987). Nutrient availability is synchronous with crop demand, however much of the available nutrients that accumulate in fallow periods may be lost from the system. Loss of resources not only limits productivity in the rainfed lowland system, but also harms rainfed ecosystems (Buresh *et al.*, 1989). Water deficit is not the only factor limiting crop production; low nutrient and fertilizer use efficiency are also the major constraints in rainfed

lowlands (Dobermann and White, 1999). Various researchers have reported that productivity and cropping intensity increase when life-saving irrigation is provided to post-rainy season crops, such as wheat, barley, rajmash and sunflower, in rainfed paddy fallow areas (Prasad *et al.*, 2000; Sarker *et al.*, 2000; Singh *et al.*, 2000). The productivity and water use efficiency of the second crop in rainfed lowland rice area can be improved by timely sowing of post-rainy season crops, providing one or two life-saving irrigations from harvested rainwater during the critical stages of the crops, by utilizing residual soil moisture and practicing improved nutrient management (Singh *et al.*, 2014). Increased water use efficiency of field crops was possible through proper irrigation scheduling by providing only the water that matches the crop evapotranspiration and providing irrigation at critical growth stages (Norwood and Dumler, 2002).

Researchers have classified the rainfed lowland ecosystem into drought-prone, drought- and submergence-prone, submergence-prone, medium-deep water and favourable "sub-ecosystems" (Khush, 1984). Research in different rainfed lowland areas, however, shows that farmers simultaneously manage a dynamic continuum of different conditions as a result of having parcels distributed over local landscapes and as a result of year-to-year climatic changes. Kar *et al.* (2006) made an attempt to increase the productivity and cropping intensity of rainfed lowland rice ecosystems of eastern India through improved management in rainfed rice crop during rainy season and by growing subsequent crops during dry winter season using residual soil moisture and supplemental irrigation at critical growth stages from harvested rain water. The technologies required for improvement in rainfed lowlands involved improving management of indigenous practices and added resources (Kirk *et al.*, 1998), but here farmers generally have no alternative to rice crops in *kharif* season because the lands are flooded during the rainy season. The main constraints to rice production are water excess and / or water deficit, often both in the same season (Widawski and O'Toole, 1990). These stresses

are often compounded by nutrient deficiencies and toxicities, so that, to some extent, water constraints can be alleviated by eliminating nutritional and toxicity constraints (Wade *et al.*, 1998). There is a scope for large-scale adoption of direct seeded rice in flood-affected and rainfed lowland areas, with significant reduction in production costs and water use and an associated increase in farmers' income. The inclusion of legumes and the effective capture of biologically fixed N and soil N through direct seeded rice system in rainfed lowlands may help in improving the rice yields of resource poor farmers (Patil *et al.*, 2001).

2.2 Direct seeded rice in rainfed lowland rice based systems

In rainfed lowland areas, when it rains immediately after seeding, farmers may encounter flooding and / or water logging which lead to severe reduction in, or complete failure of crop establishment because of the high sensitivity of rice to low oxygen stress caused by flooding during germination (Joshi *et al.*, 2013). In rainfed areas, events of waterlogging and shallow floods hinder adoption of direct seeded rice, especially when heavy rain occurs just after sowing. For example, sandy Ultisols and Alfisols predominate in the rainfed lowlands of Cambodia, Thailand and Laos, these soils have very low native fertility, organic matter, and cation exchange capacity levels (Pheav *et al.*, 1996). The poor soil quality increases the difficulty of nutrient management and restricts achievement of realistic potential yields on these soils. A unique feature of rainfed lowland systems is the alternation between anaerobic and aerobic soil conditions, which has significant consequences for root growth, nutrient availability and weed competition (Wade *et al.*, 1998).

Poor emergence and mortality of young seedlings due to submergence results in poor crop establishment and low grain yields (Ismail *et al.*, 2009). Developing varieties with ability to germinate rapidly under anaerobic conditions, with high seedling vigour and tolerance of early submergence will help enhance seedling establishment in direct seeded rice and

facilitate its adoption in rainfed areas (Ismail *et al.*, 2012). Direct seeding of rice avoids soil puddling and helps maintain good soil physical conditions that are advantageous for the following legume crop (Sharma *et al.*, 1995). It was reported that the grain yield of flood-prone lowland rice can be increased by establishing the crop early through direct seeding using high-density seed and basal N fertilization (Sharma and Ghosh, 1999). Direct-seeded crop showed better initial establishment and gave higher grain yield (3.23-3.53 t ha^{-1}) as compared to transplanted crops (1.75-1.99 t ha^{-1}) which were flooded at or soon after transplanting (Sharma *et al.*, 1995). Direct seeding may also permit a second crop to be grown before or after the main crop of rice, where otherwise it may not be possible and if the additional crop is a legume, this may result in a net input of biologically fixed N into the system (George *et al.*, 1994). Direct seeding of rice ensures better use of residual and applied N, reduces the risk due to drought, and favours intensification with post-rice legumes in drought prone low land systems (Sharma *et al.*, 2005). Poor seedling emergence and establishment are a major constraint for adopting direct seeding in rice and it is especially critical in rainfed lowlands where floods can occur immediately after sowing, creating anaerobic conditions during germination and early seedling growth (Lal *et al.*, 2016). According to Singh *et al.* (1999), during the early stages of study when rice was transplanted (1994-1995), then the rice-chickpea system had no effect on rice performance. In advanced study of this experiment, Patil *et al.* (2001) found that cropping system effects were realized from 1996 when the rice crop was established by direct seedling on dry soil. This practice provides the rice crop different growing conditions during the early crop growth stages when the soil is aerobic. During the early stages, the direct deeded rice utilizes soil nitrate N accumulated after the legume crop before it is lost by leaching or denitrification on flooding of the fields. According to Patil *et al.* (2001), direct seeded rice grows for 3-4 weeks under

aerated soil conditions, it may potentially absorb much of the mineralized soil N before it is lost.

Pala *et al*. (2000) reported that the general trends in soil water change were the same for all tillage practices (deep mold board, deep chisel, shallow cultivator and zero tillage) but that zero and minimum tillage treatment left more water at harvest for the wheat barley with deep tillage practices.

2.3 Fertigation

The term fertigation is derived from fertilizer and irrigation. Fertigation is the application of water soluble fertilizers through irrigation system (Biswas, 2010). The advantages of fertigation include slow-release of nutrients, higher N uptake by the plant to boost leaf and root weight, lower degree of ground water contamination, and higher crop yields (Cadahia, 1993). Fertigation can also reduce fertilizer application costs by simplifying operation and improving nutrient efficiency, further, it could conceivably reduce leaching or de-nitrification (gaseous) losses of nitrogen and lower the luxury uptake of nutrients by plants. Fertigation enables users to put the fertilizers in plant root zone or on canopy in desired frequency, amount and concentration at appropriate time (Kumar *et al.*, 2000). Govindan and Grace (2012) stated that fertigation in raised bed was a water saving irrigation technique that required less irrigation water for the same yield than the traditional method for rice cultivation. During fertigation, alternate wetting and drying cycles strengthen the air exchange between soil and the atmosphere (Tan *et al*., 2013).There are differences between drip irrigation and flood irrigation practice; in drip irrigation, wetting patterns from a irrigation emitter are usually considered as the radius of the wetted volume (Li *et al*., 2007a). Thus sufficient oxygen is supplied to the system to accelerate soil organic matter mineralization and inhibit soil N immobilization, all of which should increase soil fertility and

produce more essential plant-available nutrients to favour rice growth (Bouman *et al.,* 2007; Dong *et al*., 2012; Tan *et al.*, 2013). Porter *et al.* (1999) observed no effect of supplemental irrigation on soil compaction, while Bhattacharyya *et al.* (2008) observed an effect of irrigation timing on soil compaction in rice fields. Generally, additional irrigation should lead to reduced soil compaction (Vaz *et al.*, 2001; 2013), but opposing results are reported by various studies. Split application of water and N fertiliser according to crop requirements at any growth phase and the application of the fertiliser close to the roots increase the N use efficiency and reduce N loss to the environment (Kennedy *et al.*, 2013). However, the effect of fertigation on water and N dynamics in the soil may also depend on fertigation and irrigation frequency (Li *et al.*, 2004). For a given seasonal water and N supply, fertigation frequency affects the amount of water and N per application and, consequently, the soil moisture and nutrient concentration in the rhizosphere (Silber *et al.*, 2003). Biswas, (2010) indicated that fertigation technique provided better yield and quality of crops. He observed that fertigation allowed optimization of nutrient balance in soils by supplying nutrients directly to the effective root zones as per the requirement which might contribute to yield. Sivanappan (2006) reported that fertigation was a useful technology by which inorganic fertilizers could be applied to crops to increase yield. Bhuyan *et al.* (2014) reported that increase in grain yield by fertigation might be attributed to a higher level of N utilization in the plant system, hence more intense chlorophyll synthesis and more efficient translocation of assimilates to reproductive parts, because, in fertigation, nutrients are placed at very low concentrations through water and move down into the lower soil layers where the absorptive roots exist and may contribute to grain yield. They also reported that in fertigation, plant enjoys continuous nutrition because nutrients are directed to the active root zone which enables optimal match between plant requirements and nutrient supply. Wang *et al.* (2013)

reported that drip irrigation was recommended for winter wheat due to improved yield and water use efficiency.

Drip irrigation could reduce deep percolation losses of water and minimize NO_3^- leaching (Cassel*et al.*, 2001; Souza *et al.*, 2009). Watts *et al.* (1981) reported that, zero leaching loss of N is not likely to be possible in agricultural production. Drip irrigation cannot completely eliminate the deep percolation and leaching of N beyond the root zone (Gardenas *et al.*, 2005), for example, high irrigation frequency could reduce NO_3^- leaching and N rates had a significant effect on NO_3^- leaching under drip irrigation (Vazquez *et al*., 2009). Proper irrigation schedules and reducing the N rates could keep the leaching losses to a minimum (Ritter *et al*., 1989).

Drip irrigation maintain the desired concentration and distribution of ions and water in the soil (Bar-Yosef *et al*., 1999), while minimizing leaching of N from the root zone of agricultural fields (Gardenas *et al*., 2005). Proper irrigation water management practices are needed that tactically allocate water and fertilizers to minimizing N leaching to groundwater (Bar-Yosef, 1999). According to Sui *et al*. (2015) the application of water and N in excess of crop requirements contributes to the leaching of water and N below the root zone under drip irrigation. Therefore, optimal irrigation and fertilizer scheduling of drip irrigation is important to minimize leaching of N from agricultural fields.

Sharda *et al.* (2017) found that the root length density increased more in drip irrigated direct seeded rice than in flood irrigated crops and the effect was more pronounced at the depth of 15-30 cm. The large soil root systems play an important role in enhancing adaptability by absorbing nutrients and water more efficiently because of frequent irrigation in drip systems and thus easing water stress when top- soil roots are restricted by water limitation (Lilley and Fukai, 1994). It has been reported that soil water deficit often reduces

shoot growth before root growth, resulting in increased growth of roots (Kramer and Boyer, 1995). Osmotic adjustment and prolonging root cell expansion (Sharp *et al.*, 1990) have been described as causes for increased root length in mildly stressed plants than well watered plants (Jupp and Newman, 1987). Various authors suggested that, in general, crops can avoid water stress conditions by increasing water uptake if sufficient water was available within the root zone (Taiz and Zeiger, 2006) and enhancing WUE by altering the stomatal behavior (Passioura, 2002). The grain yield of direct seeded rice in drip irrigation was only slightly higher than flood irrigated crop, there was greater water saving (42%) with drip irrigation as compare to flood irrigation. The use of drip irrigation in direct seeded rice has the potential to increase irrigation water use efficiency by matching the water requirement of the crop, reducing run off and deep drainage losses, saving energy, and arresting the water table decline while ensuring the food and livelihood security (Sharda *et al.*, 2017).

Irrigation increases the soil moisture at the surface layer and the soil moisture were influenced by the depth and the irrigation water amount (Sui *et al.*, 2015). The water movement was mainly influenced by the irrigation schedule under drip irrigation, this may be because the irrigation influenced the soil moisture directly, while the fertilizer only had minimal indirect effects on moisture (Behera *et al*., 2009). Li and Liu (2011) demonstrated that a higher irrigation level yielded a larger wetted depth. However, there results further illustrated that the wetted depth was stable when the irrigation level was at 0.5–0.8 E for winter wheat. Due to the higher urea concentration, higher N applications significantly increased the NO_3^--N concentration in the upper soil layer and led to higher N residual in the root zone of wheat (Shi *et al*., 2012; Sui *et al*., 2015).

Distribution of soil moisture and NO_3^--N concentration was affected by irrigation schedule and N application rate, the deep percolation and N leaching would be different under

different irrigation and fertilizer treatments (Sui *et al*., 2015). Sexton *et al*. (1998) reported that irrigation management is even more important than fertilizer management in reducing the N leaching losses. Dong *et al.* (2012) reported that the major loss of fertilizer N occurred through ammonia volatilization amounting to 21% and 13% of the applied N in the alternate wetting and drying cycle and continuous flooding treatments, respectively. Ammonia volatilization was largely controlled by soil and floodwater pH which determined the NH_3/NH_4 ratio. Irrespective of water management, 10-12% of the fertilizer N could be recovered from the top soil (0-15 cm) after harvest, whereas 10% of fertilizer N accumulated in deeper soil horizons (15-50 cm).

2.4 Diversity and intensity of cropping systems

Intensification and diversification of cropping systems may allow improvement in the productivity and sustainability of agricultural production, but the choices to be made require integrated assessment of various cropping systems. Productivity, energy use efficiency, and nutrient up take, generally increase with increasing cropping intensity (Biswas *et al.*, 2006). The soil structure improved after cultivation of post-rice crops with suitable seeding and tillage methods (Gangwar *et al*., 2006). During the post-rainy season (dry season) irrigation facilities are not available and rainfall is meagre, therefore, subsequent cropping after wet season rice depends on the effective utilization of carry-over residual soil moisture. So conservation tillage with suitable cropping systems was helpful to maintain soil health, increase water use efficiency and check erosion (So *et al*., 2001). Inclusion of short duration low water requiring legumes (grain/green manure purpose) offered excellent opportunity to utilize carry-over residual soil moisture in rice fallows (Rahmiaanna *et al*., 2000; Kar *et al*., 2004). Higher yield of pulse after wet season rice with reduced tillage has also been reported under rainfed situation of eastern India (Pratibha *et al*., 1996 and Mahata *et al*., 1992). Sowing

just after rice harvest is considered inappropriate when there is excessive wetness of the soil leading to possible water logging of the seed, particularly where the probability of rain is high during the latter part of the rainy season (Hundal and Tomar, 1985). On the other hand, delayed sowing of legumes after rice may force the crop to encounter dry soils that are compact and hard (So and Ringrose-Voase, 2000). Aslam *et al*., (1999) found that no-tillage produced 10 per cent more wheat grain compared to farmers' practices of minimum three ploughings with planking in rice-based cropping system. Mosaddeghi *et al*., (2009) observed that no-tillage practice can gradually increase mechanical impediment of the surface soil, limiting the distribution of roots in the upper soil profile. Legumes are also known to be effective in increasing and conserving mineralized soil nitrogen for subsequent use of rice (Buresh *et al*., 1989; Singh *et al*., 1999). The effects of legumes observed in the study by Sharma *et al*. (2005) must be attributed to belowground processes and leaf fall because aboveground residues were removed at harvest. Root and stem nodules of legumes can contain significant amount of N varying from 13 to 50 kg/ha (Ladha *et al*., 1996). There are however conflicting reports on the benefits of food legumes to a subsequent rice crop when the aboveground legume biomass is removed (De *et al*., 1983). Even with removal of aboveground legume biomass at maturity, leaf fall during crop development can contribute legume N to the subsequent rice crop (Buresh and De Datta, 1991), a process that could be more important for chickpea than *moong*. Retention of crop residues on soil surface, nutrient application through fertilizers and organic manures, inclusion of legumes in crop rotation and adoption of minimum/no tillage practices play an important role to sustain soil fertility, improving fertilizer/water use efficiency, physical conditions of soils and enhancing crop productivity (Mohammad *et al*., 2003). The rice-chickpea system produced significantly (1%) higher grain, straw and total biomass than the fallow-rice system, and had significantly higher dry matter and N accumulation at tillering, panicle initiation, heading, and maturity stages.

However, the harvest index remained unaffected by the cropping system (Patil *et al*., 2001). Campbell *et al*. (1992) found that rotational benefits of lentil were apparent in the first two years of experiment, results of the effects of legumes in cereal rotations may not always be immediate, and that long-term experiments, i.e. 5–15 years, may be necessary for understanding the N dynamics of such systems. Low barley yields can be attributed mainly to low soil pH (less than 5.5) and deficiency of nutrients, especially N and P, due to continuous cropping of cereals (Agegnehu *et al*., 2014a) and low levels of fertilizer application (Agegnehu *et al*., 2011). Campbell *et al*., (1992) reported that the benefits of lentil to soil N supply and grain yield and nitrogen content of wheat were cumulative and increased with succeeding phases of the rotation. The benefits were close to zero after two lentil crops (4 years of the rotation), increasing to about 40 kg N/ha after four crops (8 years). The causes of low yields of dry season crops after rice are often poor crop establishment and inferior root growth due to adverse physical conditions of the soil which, in turn, are caused by the wet cultivation (puddling) undertaken for paddy rice (So and Woodhead, 1987).

2.5 Effects of fertilizer application and irrigation on soil conditions under rainfed lowland rice based cropping systems

Cropping system and crop residue management affected tilth by changing the soil consistency. They had pronounced effects on the range of soil moisture levels optimum for ease of tillage in sandy clay loam soil (Fagi and De Datta, 1982). Standing rice stubbles of different rice habitats could change the characteristics of the soil surface, and hence influence the soil thermal properties by reducing soil evaporation (Cutforth and McConkey, 1997) that renders more water available to the crop. The plant nutrient uptake and soil physical conditions are dependent on soil organic matter that affects all three aspects of soil fertility, namely chemical, physical and biological fertility (Chan *et al*., 2008). Leguminous residues decomposed faster because of low C: N ratio, increased the mineral N pool in soil and

contributes to yield improvement (Mohammad *et al*., 2012). Evans *et al*., (1991) verified that N is a key factor in the response of cereals following legumes compared with cereals following non legumes. Chalk (1998) reported from a review that cereals derive both yield and N benefits from rotations with grain legumes as compared with cereal monoculture.

For alternate wetting and drying practices, the fields are managed as irrigated lowland rice but the top soil layer is allowed to dry out to some degree before irrigation is applied again (Belder *et al.*, 2004). The number of days under non-flooded soil conditions can vary depending on plant development stages and availability of water (Dong *et al.*, 2012). The alternating oxic and anoxic top soil conditions imposed by alternate wetting and drying irrigation may lead to increased N losses from nitrification-denitrification processes (Nicolaisen *et al*., 2004; Liu *et al*., 2010). Reddy and Patrick (1975) found that about 24 per cent of the total N was lost in a laboratory experiment after 32 cycles of alternate anoxic and oxic soil conditions. Likewise, greenhouse (Eriksen *et al*., 1985) and field studies (Liu *et al*., 2010) have shown that alternate wetting and drying can increase fertilizer loss via denitrification, whereas other researchers have shown that alternate wetting and drying does not enhance nitrogen loss (Khind and Ponnamperuma, 1981; Fillery and Vlek, 1982). Although denitrification loss may sometimes be significant, ammonia (NH_3) volatilization is typically the most important pathway of fertilizer N loss from irrigated rice field (Eriksen *et al*., 1985; Fillery and Vlek, 1982; De Datta *et al*., 1991). The conversion of ammonium to nitrate is typically restricted by limited oxygen supply in flooded soils, and ammonium typically accumulates after soil flooding because of continued mineralization and reduced nitrification (Buresh and De Datta, 1991; Witt and Haefele, 2004).Ventura and Yoshida (1977) found that ammonia volatilization was lower in alternate wetting and drying than continuous flooding conditions. Contradicting this, Patel *et al*. (1989) demonstrated that ammonia volatilization was almost the same for alternate wetting and drying and continuous

flooding if the water level was kept shallow and that increasing the water level reduced volatilization significantly. High irrigation water level may even reduce ammonia loss, most likely due to an ammonium ion dilution effect (Win *et al*., 2010). Shallow irrigation water has been suggested to lower ammonia volatilization due to enhanced ammonium binding in the soil (Li *et al*., 2008). Crops grown in lowland soils after rice may suffer from deficiencies of plant nutrients and from a lack of suitable micro-organisms such as *Rhizobia* or VAM, which may not survive prolonged waterlogged conditions (So *et al*., 2000).

In rice based cropping systems after rice harvesting drying of the soil leads to re-oxidation of reduced substances such as ferrous iron and sulfides, which cause decrease of soil pH. Application of nitrogenous fertilizers through fertigation leads to nitrification, which is likely to be a major source of soil acidification (Biswas *et al*., 2006). Cropping systems with varying root growth characteristics create various levels of soil aeration, which may also decrease soil pH (Biswas *et al*., 2006). Soil solution pH is dependent on mineral weathering and mineral weathering increases pH by releasing Ca, Mg and K (Smith *et al*., 1994, Michaelson and Ping 1987). Another research also reported that P and K fertilization increased N utilization and resulted in decreased soil acidification i.e. increased pH value (Michaelson and Ping, 1987). Electrical conductivity of soils is often related to soluble salts such as nitrates and the concentration of these is much affected by N fertilizer use and N losses due to leaching and denitrification (Smith and Doran, 1996).

Nitrogen application with fertigation in rice followed by various cropping systems like-rice followed by legumes influence the accumulation, dynamics, uptake and carryover of soil inorganic N in soil (Buresh and De Datta, 1991). Buresh *et al*. (1989) reported that nitrogen accumulates as nitrates during the post-rice legume growth and the subsequent dry season. These nitrates are however prone to loss of nitrogen by leaching and denitrification during the onset of wet season rains and following the submergence of the soil for establishment of rice

crop. The inclusion of legumes and the effective capture of biologically fixed N and soil N through direct seeded rice system in rainfed lowlands may help in improving the rice yield of resource poor farmers. Singh *et al.* (1999) found that soil N accumulation from a post rice legume crop is prone to losses by denitrification and leaching during land preparation for puddling and transplanting of rice. According to Patil *et al*. (2001), the potential of direct seeded rice to accumulate nitrogen is more in rice chickpea cropping system than rice fallow. So the use of soil nitrogen derived from the legume, rice yield, dry matter and nitrogen accumulation were significantly higher in rice legume cropping system. The duration of the flooded and non-flooded period or the transition from aerobic to anaerobic aeration status has a major impact on accumulation and dissipation of soil mineral N (Buresh and De Datta, 1991; George *et al*., 1992). Alternate wetting and drying during a rainfed lowland rice crop is the main problem. In this situation it is difficult to distinguish such effects from other effects of wetting and drying, such as water stress and nitrification-denitrification losses (Wade *et al*., 1997). Fertigation can improve N utilization and there are reduced losses of N fertilizer through nitrate leaching. At the same time plants take up more N when applied by fertigation than when applied through broadcasting or placement and the overall root activity improves the mobility of nutrient elements and their uptake. The fertigation technique is used mainly with N fertilizers (Bhuyan *et al*., 2014).

Irrigation and drainage water should be appropriately managed to reduce runoff P losses from rice-wheat cropping systems as rice growing season constitutes a high risk of P losses when heavy rainfall occurs shortly after P application and field ponding water (5-15 cm depth of water) level exceeds the field bund. The bunds are constructed to enclose the ponding water as needed by rice, but it also seemed to have prevented some of the P losses (Jian *et al*., 2016). Less than 20 per cent of applied P is recovered by crops in the first year of growth at early stage after fertilization, because most P applied to soil is converted into unavailable

forms that cannot be easily absorbed and used by plants; therefore, farmers often apply additional P fertilizer to support high grain yields (Wang *et al*., 2010).

Rice soils in the Indo-Gangetic plains are rich in illites, which fix K^+ under both dry and moist conditions (Mahajan *et al*., 2012). Malvolta (1983) reported that when soils were mixed and shaken with a K solution, K+ fixation was 25 per cent, while it was 68 per cent when K^+-saturated soils were dried. K^+ fixation was 2–3 times greater after drying than after wetting. This suggests that intermittent drying conditions in direct seeded rice may cause temporary K deficiency in rice. The release of non-exchangeable K appears to have increased with plant growth and K uptake is higher in direct seeded rice than transplanted rice. K uptake decreases the concentration of K in the soil solution near root surfaces and this induces the release of K held on the external surfaces of soil particles in exchange for other cations in solution and the more gradual release of K held within clay interlayers (Winhardjaka *et al*., 1999).

Maintenance of soil organic carbon is recognized as a strategy to reduce soil degradation. Soil organic matter as well as soil organic carbon are important in maintaining several soil properties and can be controlled by management practices, including the choice of cropping, management of crop residues and methods and intensity of tillage (Voroney and Angers, 1995). Legume-based cropping sequences such as soybean–wheat (S–W), soybean–lentil (S–L) and soybean–pea (S–P) and conservation tillage or zero tillage have the potential to enhance soil organic carbon content in the soil surface but this has no effect on soil organic carbon concentration within whole soil in the sub-surface soil layer (Bhattacharyya *et al*., 2009). Particle size fractions provide a rough differentiation between young (active) and older (intermediate and passive) SOM pools (von Lutzow *et al*., 2007). The sustainability of a production system can also be judged by change in soil organic matter content under a set of management practices, because organic matter enhances soil quality by improving soil structure, nutrient storage, and biological activity (Bragato and Primavera, 1998), and also

because the readily decomposable fraction of organic matter is sensitive to short term modifications in management practices.

Soil aggregate as the basic unit of soil structure, has a great influence on the physical, chemical, and biochemical processes of soils (Lu and Li, 2002). Well aggregated soil structure is the most desirable condition for plant growth because it has beneficial effects on soil moisture status, nutrient dynamics, and soil tilth (Oades, 1984). The distribution of soil organic carbon (SOC) in different aggregate size classes (i.e. micro-, meso-, and macro-aggregates) may affect erosion, and more rapid loss may occur from macro-aggregates than micro-aggregates (Eynard *et al*., 2005). The water stable aggregation helps to measure the soils susceptibility to erosion, compaction and other disruptive forces. Raindrop impact and surface flow of water are primary sources of energy causing disintegration of soil aggregates in the field and thus the resultant soil erosion. Zero tillage increased bulk density, mean weight diameter and the proportion of macro-aggregate fractions (2– 4.75 mm, 0.25–2.0 mm) in the soil compared to conventional tillage in the surface soil layer, but not in the sub-surface soil layer. Management practices, such as conservation tillage and legume-based cropping sequences, have the potential to enhance SOC and total soil N (TSN) content and improve soil aggregation as it adds more leaf-fall, nodule and root biomass to the soil (Bhattacharyya *et al*., 2009).

Zhang *et al*. (2013) even observed an increased BD after alternating flooding and drying cycles. Moderate compaction may speed up the rate of seed germination and reduce water loss, where as excessive compaction results in higher soil strength and does not provide adequate pores and spaces for root elongation (Tolon-Becerra *et al*., 2011). Rice alternated with upland crops significantly improved physical quality of soil in terms of bulk density, soil porosity, soil aggregate stability, and soil penetration resistance in comparison to the traditional rice mono-culture practice, especially in the 10–20 and 20–30 cm depth layers

(Linh *et al*., 2015). Lowery and Schuler (1994) showed that penetration resistance and bulk density increased with increasing level of compaction.

Penetrometers are simple instruments which measure the compaction or soil penetration resistance (or cone index or mechanical impedance). Penetration resistance has a correlation with other soil physical properties like water holding capacity, porosity, bulk density, texture, soil organic matter content, soil structure, presence of stones and clay mineralogy etc. (Gerard *et al*., 1982; Bradford *et al*., 1986; O'Sullivan *et al*., 1987; Vaz and Hopmans, 2001). Penetrometer measures the force required to insert a cone tip into the soil. Penetration resistance (PR) is calculated by dividing this insertion force by the base area of the cone. Penetrometers have a potential relationship with soil physical conditions for root elongation (Taylor and Gardner, 1963; Gerard *et al*., 1982), root penetration (Taylor and Ratliff, 1969) and plant growth (O'Sullivan and Ball, 1982; Bradford *et al*., 1986; Lowery and Morrison, 2002). Penetrometers can be used to measure the spatial variation in surface and subsoil compaction (Hakansson and Voorhees, 1998; Clark, 1999), study about various tillage systems and best management practices (Cassel *et al*., 1978; Unger and Jones, 1998; Vazquez *et al*., 1991), seed emergence (Chi and Tessier, 1995), and soil crust formation (Baumhardt *et al*., 2004). In spite of these there are several reports on the relationship between the effects of long-term application of organic and mineral fertilizers on soil bulk density and penetration resistance (Celik *et al*., 2010). Decrease in bulk density (4.3–6.9 %) and penetration resistance (15.9–30.7 %) and increase in organic carbon content (23.6–35.3 %), water stable aggregates (16.1–32.5 %) in conservation agriculture compared to conventional tillage system have been reported (Parihar *et al*., 2016). Bulk density and penetration resistance have been used to characterize soil compaction which influences the structural characteristics and functions of soils (Hakansson and Lipiec, 2000; Abu-Hamdeh, 2002). Several studies have revealed close correlations of penetration resistance with root elongation (Laboski *et al*., 1998; Lampurlanes

and Cantero-Martinez, 2003; Pabin *et al*., 1998) and crop yield (Whalley *et al*., 2007). At high water contents, the penetration resistance is practically insensitive to changes in bulk density, and the water content has little effect in cohesion less soils (Bengough *et al*., 2001). Correlation between particle size and penetration resistance were presented by Kasim *et al*. (1986), where coarse textured soils showed greater penetration resistance when compared to fine textured soils. No-tillage with residue, no-tillage after wheat, and conventional tillage after sorghum under controlled traffic conditions had no significant effect on penetration resistance, bulk density, and water content (Unger, 1996). Subsoil compaction can be reduced by natural physical processes such as freezing and thawing (FT) and wetting and drying (WD) cycles, as well as by biological activity (Hakansson *et al*., 1987).

2.6 Water and nutrient use efficiency under improvised rainfed lowland rice based cropping systems

Increased water use efficiency of field crops was possible through proper irrigation scheduling by only providing the irrigation at the time which matches crop evapotranspiration and at critical growth stages of the crops (Hunsaker *et al*., 1996; Norwood and Dumler, 2002). The amount of water use is directly proportional to the amount of water available in the soil profile. The productivity and WUE of subsequent crops in lowland rice areas can be improved by practicing timely sowing of post-rainy season crops and by providing required lifesaving irrigation during the critical stages of the crops. The rainy season crops provide necessary environment for increasing the yield potential for growing *rabi* season crops in rainfed lowland rice ecosystem by utilizing residual soil moisture, practicing improved nutrient management, and applying limited irrigation from harvested rainwater (Singh *et al.*, 2014). While increasing the water productivity of rice is important, water productivity and profitability of the entire cropping system is of ultimate importance and growing winter crops

after rice and permanent bed systems offer potential benefits of increased productivity of crops traditionally grown in rotation with rice, increased cropping diversity and flexibility (Humphreys *et al*., 2006). Mohammad (2004) reported that fertilizer N utilization efficiency was lower with soil application than fertigation and that fertigation also improved the water use efficiency. Increasing soil water availability positively affected nutrient mineralization, and physical transport of ions in soil, which should increase plant-available nutrients (Vitousek, 1982; Zak *et al*., 1994; Burke *et al*., 1997; Schimel *et al*., 1997), resulting in greater gains in biomass and nutrients (Patterson *et al*., 1997). Efficient use of leftover soil moisture and nutrients through resource conservation technologies for the post-rice crop can convert lowland rice farming into a profitable enterprise by enhancing the productivity and profitability from these crops in rice-fallows (Musa *et al*., 1998; Maclean *et al*., 2002).The available soil water storage in most soils after rice harvesting ranges from 150 to 200 mm and researchers concluded that during the post-rainy season (November–March), rice-fallow lands can be brought under double cropping through the carry-over of residual moisture (Musa *et al*., 1998; Das *et al*., 2014). Early crop establishment in aerobic soils, such as by direct seeding, favours higher root and shoot growth, which enables water extraction from a larger soil volume and deeper layers compared to transplanted rice (Naklang *et al*., 1996).

Biswas (2010) reported that fertigation increased fertilizer use efficiency due to improved availability of nutrients and their uptake by crops. Rajput *et al*. (2010) showed that nitrogen use efficiency in fertigation was 95 per cent whereas broadcasting of fertilizers resulted in an efficiency of only 40 per cent. He speculated that higher nitrogen use efficiency in fertigation over broadcasted fertilizer was due to proper dose and timing of fertilizer application. Kafkafi (2006) indicated that fertigation improves fertilizer use efficiency by applying nutrients only to the active root zone, which reduces losses of nutrients through leaching or soil fixation. Fertigation can improve N utilization and there are reduced losses

through nitrate leaching. At the same time plants take up more N by fertigation than broadcast and the uptake of nutrients is also enhanced agronomic efficiency of N. In addition, fertigation was shown to enhance overall root activity, improve the mobility of nutritive elements and their uptake. Fertilizer-N efficiency is relatively low in irrigated lowland rice systems because applied inorganic N is rapidly lost from the soil-floodwater system by volatilization and denitrification (De Datta and Buresh, 1989). There are reports showing that the adoption of Alternate Wetting and Drying (AWD) based technologies could reduce total cumulative plant N and N use efficiency (NUE) by stimulating N losses through increases in ammonia volatilization, nitrification and denitrification (Zou *et al*., 2007). But some studies have shown that AWD based irrigation could not increase N loss due to the reduction in vertical NH^{4+}-N and total N leaching, and accordingly, could not decrease NUE (Wang *et al*., 2011). Fertigation–irrigation frequency may affect crop biomass accumulation and partitioning, i.e. root growth and the shoot/root, along with the consequent changes in water and N uptake efficiency and yield (Silber *et al*., 2003; Zotarelli *et al*., 2009). Excessive irrigation in DSR may increase N loss in soil through leaching and increase nitrate pollution in underground water. So, improved irrigation management practices leading to increased fertilizer N-use efficiency (NUE) can reduce the potential for nitrate pollution in groundwater (Bijay-Singh *et al*., 1995; Cassman *et al*., 2002). The use of N can be increased by balanced application of N, P, and K and by more frequent light irrigation (Bijay-Singh *et al*., 1995;). Many studies have investigated the productivity and water-use efficiency of direct seeded rice (Mahajan *et al*., 2011), with the interactive effect of irrigation and fertilizer amounts. According to Kato *et al*. (2016), in unsubmerged soil conditions, N and P uptake and N-use efficiency (biomass/N uptake) is positively correlated with biomass accumulation at heading stage. The partial factor productivity from applied nutrients is a useful measure of nutrient use efficiency because it provides an integrative index that quantifies total economic output

relative to utilization of all nutrient resources in the system, including indigenous soil nutrients and nutrients from applied inputs (Cassman *et al*., 1996). According to Saha *et al*. (2009) in both the Boro and T. Aman seasons, agronomic efficiency (kilogram grain yield increase per kilogram of applied K), physiological efficiency and partial factor productivity of K decreased with increasing K level regardless of K sources. Saha *et al*. (2009) also reported that the highest agronomic efficiency and physiological efficiency was observed with the treatment having K application of 66 kg/ha without rice straw incorporation in both boro and T aman seasons. A simultaneous reduction in irrigation or N availability increases the harvest index because excessive vegetation growth is restricted (Zegbe *et al*., 2004). As already discussed for total above-ground biomass, the fertigation–irrigation frequency may increase the N uptake efficiency, while the fate of the residual N in the soil after harvest cannot be predicted as it depends on other environmental and agronomical aspects such as the rainfall regime and use of cover crops in fall-winter (Benincasa *et al*., 2010). Sun *et al*. (2012) using differential responses to physiological and biochemical changes of rice elucidated that higher activities of ammonia assimilation enzymes (glutamine synthetase, glutamate synthase, and glutamate dehydrogenase) which are the main enzymes involved in plant N metabolism were obtained under intermittent irrigated on that flooded irrigation.

2.7 Productivity and nutrient dynamics of rainfed lowland rice based cropping systems as affected by fertilizer application and irrigation

Castellini *et al*. (2015) reported that small decreases in bulk density (0.014 Mg m^{-3}) may result in substantial modifications in soil water retention close to water saturation. Previous studies suggest that an integrated soil fertility management approach may have more sustainable agronomic and economic impact than a focus on chemical fertilizer alone (Agegnehu *et al*., 2014b). In some areas of eastern India, farmers establish the post-rice crops by broadcasting the seeds within the standing rice crop under conditions of ample soil

moisture about 15–20 days prior to the harvest of rice. This system of crop establishment foregoes any tillage and is called relay cropping. In this system, farmers usually obtain much less yield (0.2–0.3 t/ha) from post-rice crops and it might be due to unfavourable physical conditions of the soil which inhibit crop growth and nutrient uptake in rice fallow (Kar and Kumar, 2009). Vadez *et al*. (2012) also reported that supplementary irrigation would greatly increases chickpea yield and showed across 14 locations of the chickpea growing areas in India that 30 mm of irrigation applied at the beginning of seed growth would increase yield on an average by 30 per cent.

Availability of nitrogen in the soil could limit nitrogen supply to the crop. A maximum daily nitrogen accumulation was imposed of 0.45 g m^{-2} day^{-1}. This maximum value was observed by Soltani *et al*. (2006) under potential growth conditions in the field. The greatest changes in yield were obtained by irrigating the crop with 30 mm at the beginning of seed growth. The average yield gain across all locations was 29 per cent and the high yield benefit was achieved across all yield levels. These results indicated that some benefits come from growing the crop in soil with a higher depth of effective water extraction, which require faster root growth in very low rainfall environments, but the greatest yield benefit would result from modest irrigation at the beginning of seed growth.

Belder *et al*. (2005) compared fertilizer-N uptake and recovery in flooded and aerobic rice systems, and reported that aerobic rice was more limited by N than flooded rice because unaccounted-for N (i.e., not used) was higher in an aerobic system than in a flooded rice system. More N uptake by rice due to the application of P and K fertilizers along with N fertilizer application is seen to contribute more prolific root growth and LAI, resulting in higher photosynthetic efficiency. This also contributes directly to an increase in the number of panicles m^{-2} and grains $panicle^{-1}$, and better grain setting (higher percentage of filled grains) (Mahajan *et al*., 2012).

The addition of P fertilizer at soil moisture tension of 20 kPa plays a role in improving P uptake that also caused an improvement in WUE and NUE by increasing root proliferation (Mahajan *et al*., 2012). He *et al*. (2011) found that in aerobic rice, compensation for the water shortage caused by increased P application was significant, and; as a result, the yield of rice in soil with 80 per cent of water-holding capacity (aerobic soil) exceeded that in waterlogged soil. Therefore, the synergism of soil moisture content and P application rate was expected to be more significant in rice than in other crops grown in aerobic soil conditions since usually rice is cultivated in waterlogged soil in which available soil P is generally in optimal condition (Kirk *et al*., 1998). Zhou *et al*. (2002) found that P application increased plant height, number of tillers, and root volume of rice grown in aerobic soil. Correlation studies with the addition of P and K along with N resulted in higher WUE, N uptake, and LAI, and ultimately improved yield-contributing characters and yield than without the application of P and K, however, with the application of N alone, WUE did not have any relationship with yield-contributing characters (Mahajan *et al*., 2012). The application of P to soils and its effect on WUE has been documented only for a limited number of crops, for example, chickpea (Singh and Bhushan, 1980). The concentration of nutrients like nitrogen, phosphorus and potassium in both grain and straw implied great influences of crop management practices, soil types and climatic conditions on nutrient absorption in plant. Phosphorus is a critical nutrient required for crop growth, development and grain production. Wang *et al*. (2010) reported that less than twenty per cent of applied P is recovered by crops in the 1st year of growth, because most P applied to soil is converted into unavailable forms that cannot be easily absorbed and used by plants. Farmers often apply additional P fertilizer to support high grain yield. So excessive P application may exacerbate environmental degradation and reducing P application by rice producers is desirable from an environmental point of view. Cassman *et al*. (1993) found a linear relationship between N and P assimilation in soybeans

with as much as a 10-fold increase in N accumulation per unit increase in P accumulation. Therefore the value of P fertilizer added to legumes may be enhanced by the additional N generated in the system. N accumulation by BNF- dependent plants will be less than that by mineral N-dependent plants, because nodules are not fully operational during early vegetative and late reproductive growth stages, and therefore BNF dependent plants are likely to be N-deficient during these stages (George and Singleton, 1992).

2.8 Rice production under rainfed conditions

Although, there is no dearth of scientific literature about rainfed rice cultivation with its constraints, potentials and technological options, an attempt has been made in this section to collate some recent publications that relate to the constraints for which the present research is targeted. Rainfed areas supply about 58 per cent of global food production and play an important role in food security (Seck *et al*., 2012). Rice is one of the major crops grown and consumed in rainfed areas, and rainfed cultivation accounts for about 25% of global rice production. Due to its dependence on climate, rainfed rice cultivation is vulnerable to changes in temperature and rainfall. Drought reduces plant transpiration rates and may result in leaf rolling and drying, reduction in leaf expansion rates and plant biomass, immobilisation of solutes and increased heat stress of leaves (Jagadish *et al*., 2010; Van Oort *et al*., 2011). In rainfed areas, water logging and shallow floods hinder adoption of direct seeded rice, especially when heavy rain occurs just after sowing, so poor emergence and mortality of young seedlings caused by submergence result in poor crop establishment and low grain yield (Ismail *et al*., 2009). In transplanted rice, ammonium is the dominant form of available N, whereas, in aerobic rice systems, the dominant form of N is nitrate, which results in different pathways of N losses and N availability (Belder *et al*., 2005). They also reported that yield limitations imposed by nitrogen supply in soil are more pronounced under aerobic conditions than under flooded conditions. Zaidi *et al.* (2017) reported from studies conducted through

on-farm trials and village level demonstrations that the application of *Trichoderma harzianum* strain S2 along with IRRI (International Rice Research Institute) improved BMP (best management practices) was most effective for enhancing the yield and yield attributes of stress tolerant rice varieties. With this intervention, the highest grain yields of 4.91 t ha^{-1} for *Sahbhagi Dhan* during 2013 and 4.81 t ha^{-1} for *Swarna-Sub1* during 2014 were obtained. They advocate for an effective use of microbes along with inherent abiotic stress tolerance of the crop and best management practices, to alleviate stresses under field conditions for rainfed rice. Mottaleb *et al*. (2015) reported that in Asia nearly 50 per cent of rice farmland area is under rainfed rice ecosystem where drought and submergence are the major limiting factors to production. Based on analysis of *MODIS* data, they demonstrated that both drought and submergence significantly affected rice production and that on an average, a one percent increase in drought affected area at district level reduces *Aman* season rice production by approximately 1382 kilograms per household. Similarly, a one percent increase in drought area reduces rainfed *Aus* season rice production by approximately 693 kilograms per household.

Materials and Methods

MATERIALS AND METHODS

The present study entitled "**Soil properties and nutrient uptake by rice under different fertigation regimes in rice based cropping systems.**" was carried out in an on-going fertigation experiment involving rainfed rice based cropping systems initiated in June, 2014 at the farm of Bihar Agricultural University, Sabour, Bhagalpur, Bihar, India. The present investigation was conducted during the third rice crop in the system (*kharif,* 2016). The details of field experimentation and methodology adopted during the course of investigation have been described under the following heads:

3.1 Site characteristics

3.1.1 Location

The experimental farm of Bihar Agricultural College, Sabour, Bhagalpur comes under the Middle Gangetic plain region of Agro-climatic Zone IIIA and it is situated at the geographical coordinates of 24^0 13´ 45´´ N latitude, 87^0 02´ 48´´ E longitude and an altitude of about 25 m above mean sea level and is characterized as sub-humid zone of Bihar.

3.1.2 Climate and weather

Bhagalpur is located in sub-tropical climate characterized with hot desiccating summer, cold winter and moderate rainfall. May is the hottest month with an average maximum temperature of 35 to 39˚C. January is the coldest month of the year with mean minimum temperature varying from 5 to 10˚C. The average annual rainfall is 1231.4 mm, precipitating mostly between mid June to mid October (during south west monsoon) (Kumar and Kumar, 2014). The meteorological data recorded during the experimentation period (2016) based on observations made at the meteorological observatory of the Bihar Agricultural University, Sabour. A summary of the actual weather prevailing during the crop growing period in 2016 is appended in Appendix I and a summary displayed in Figure 3.1.

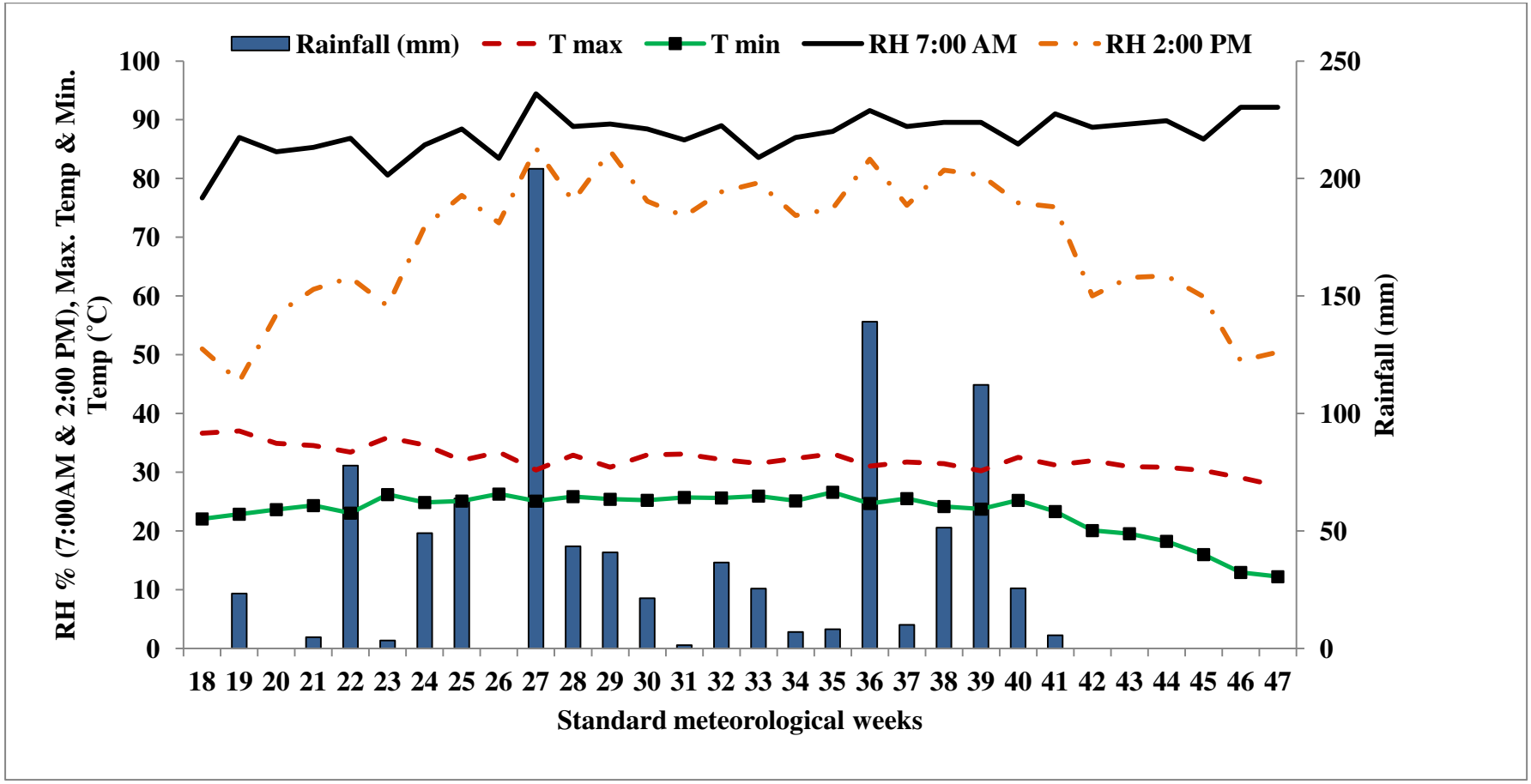


Figure 3.1: Cumulative weekly rainfall (mm), mean weekly maximum temperature (^{0}C), mean weekly minimum temperature (^{0}C) and mean weekly relative humidity (%) at 7:00 AM & mean weekly relative humidity (%) at 2:00 PM as measured at the agro-meteorological observatory, BAC, Sabour for the rice growing period in 2016 represented as per the standard meteorological weeks.

3.1.3 Common cultural practices adopted for rice cultivation

The field left fallow after the harvest of *rabi* season crops in 2015-16 during summers was treated with a spray of Glyphosate @ 1 kg a.i. ha^{-1} + 2,4-D @ 1 kg a.i. ha^{-1} for clearing the standing weeds in the experimental field and bunds. The seeds of rice variety *Sahbhagi Dhan* procured from the Directorate of Seeds and Farms, BAU, Sabour were drilled in rows 30 cm apart @ 30 kg ha^{-1} along with calculated amounts of MOP and SSP based on the general recommended dose of fertilizers of 40 kg P_2O_5 ha^{-1} and 20 kg ha^{-1} for rainfed rice. Nitrogen was applied as urea @ 75%, 50% and 25% of the rainfed RDF of 80 kg ha^{-1} in the respective treatments (i.e. 60, 40 and 20 kg/ha N respectively). One third of the respective dose of nitrogen was drilled along with the P and K fertilizers before sowing of seeds in the same rows. The other two split doses of nitrogen were applied through fertigation at the time of panicle initiation and active tillering respectively. All visible weed plants were manually uprooted as and when observed in the experimental field. The harvesting of the crop was done from the base of the stem, keeping the net plot harvest separated from the border areas, sun dried for 2-3 days, weighed and threshed to estimate the grain and straw yield.

3.1.4 Common cultural practices adopted for cultivation of post rice crops during the previous two years

In *rabi* season after harvesting of the wet season rice crop, the field was treated with a spray of Glyphosate @ 1 kg a.i. ha^{-1}+ 2,4-D @ 1 kg a.i. ha^{-1} for clearing the standing weeds in the experimental field and bunds. The seeds of various post rice crops were drilled along with the recommended doses of fertilizers in rows by line sowing in sub plots without any primary tillage. The respective doses of fertilizers in terms of N, P_2O_5 and K_2O are given in table 3.1. All visible weed plants were manually uprooted as and when observed in the experimental field. The harvesting of the crops was done from the base of the stem, keeping the net plot

harvest separated from the border areas, sun dried for 2-3 days, weighed and threshed to estimate the grain and straw yield.

3.1.5 Soil

Before the initiation of the experiment in 2014, the soils were neutral in reaction with a pH value of 6.9, electrical conductivity value of 0.17 dS m^{-1}, 0.35 % organic carbon (Allison, 1965), and available N (Subbiah and Asija, 1956), P_2O_5 (Olsen *et al*., 1954) and K_2O (Jackson, 1973) of about 217.8, 27.8 and 131.3 kg ha^{-1}, respectively. The soil pH and EC measured from samples drawn from the depths of 0-15 cm, 15-30 cm and 30-45 cm before rice crop establishment were 7.26, 7.38 & 7.37 and 0.17, 0.14 and 0.12 dS m^{-1}, in the same order. The soil pH and EC measured from samples drawn from these depths after the harvest of the rice crop were found to be 7.26, 7.34 and 7.34 and 0.13, 0.13 and 0.13 dS m^{-1}, in the same order. The soil textural class was determined using International Pipette Method (Day, 1965) in triplicate soil samples each drawn from the depths of 0-15 cm, 15-30 cm and 30-45 cm. The mean sand, silt and clay contents (%) at the depths of 0-15 cm, 15-30 cm and 30-45 cm were 51.3, 20.7 & 27.9; 51.2, 21.4 & 28.4; and, 50.3, 18.0 & 31.7, in the same order. These correspond to a soil textural class of sandy clay loam at all depths. Taxonomically these soils are classified as Inceptisols.

3.3 Treatments and experimental details

An experiment on fertigation in zero till direct seeded rice based cropping systems involving zero till direct seeded durum wheat, barley, lentil, chickpea, linseed and lathyrus laid out in a split plot design with three replications was initiated in the *kharif* season of 2014. However, only four crops namely durum wheat, barley, lentil and chickpea formed a part of the present investigation.

The experiment involved three levels of fertigation in main plots designated as

Table 3.1: The varieties, seed rates and fertilizer application rates for various post rice crops being used in the experiment.

S. No.	Crop	Variety	Seed rate (kg ha^{-1})	Fertilizer N (kg ha^{-1})	Fertilizer P (kg ha^{-1}, P_2O_5)	Fertilizer K (kg ha^{-1}, K_2O)
1.	Durum wheat	HD-8627	100	120	60	40
2.	Barley	Local	80	80	60	40
3.	Lentil	Arun	45	18	46	-
4.	Chickpea	BG-372	80	18	46	-

W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops;
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops;
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crops.

The sub plots consisted of various rice based cropping systems designated as

C_1=Rice-Durum Wheat,
C_2=Rice-Barley,
C_3=Rice-Chickpea,
C_4=Rice-Lentil

The size of each sub-plot was 4.0 m x 4.2 m and was separated from the surrounding plots by a bund measuring 0.5 m in width. Each main plot consisted of 6 sub plots in the original layout, out of which only four sub-plots are a part of the present investigation; and, each main plot was also separated by the neighbouring plots by a bund measuring 0.5 m in width. A layout of the experimental field is presented in figure 3.2. All crop rows were spaced 30 cm apart and drip laterals of an inline fertigation system were laid out 60 cm apart so that each lateral catered to fertigate one crop row on each side.

3.3 Soil sampling and analysis

Composite profile soil samples were collected from all plots in 15 cm depth increments up to 45 cm depth during May, 2016 representing the duration between the end of 2nd year *rabi* and the initiation of third year *kharif* season. Another corresponding set of depth wise soil samples were collected from each plot after the harvest of rice in November, 2016. These samples were air dried and ground to pass through a 2 mm sieve and stored for analysis. Another set of sampling involved sampling of field aggregates from the surface soil both before rice crop establishment as well as after the harvest of the rice crop to determine the wet aggregate stability of aggregates. Soil aggregates were collected using hand shovel from the surface of each plot during July 2016 (before paddy sowing) and in November 2016 (after harvest of paddy) for evaluating the wet aggregate stability (as measured by the indices of MWD and GMD

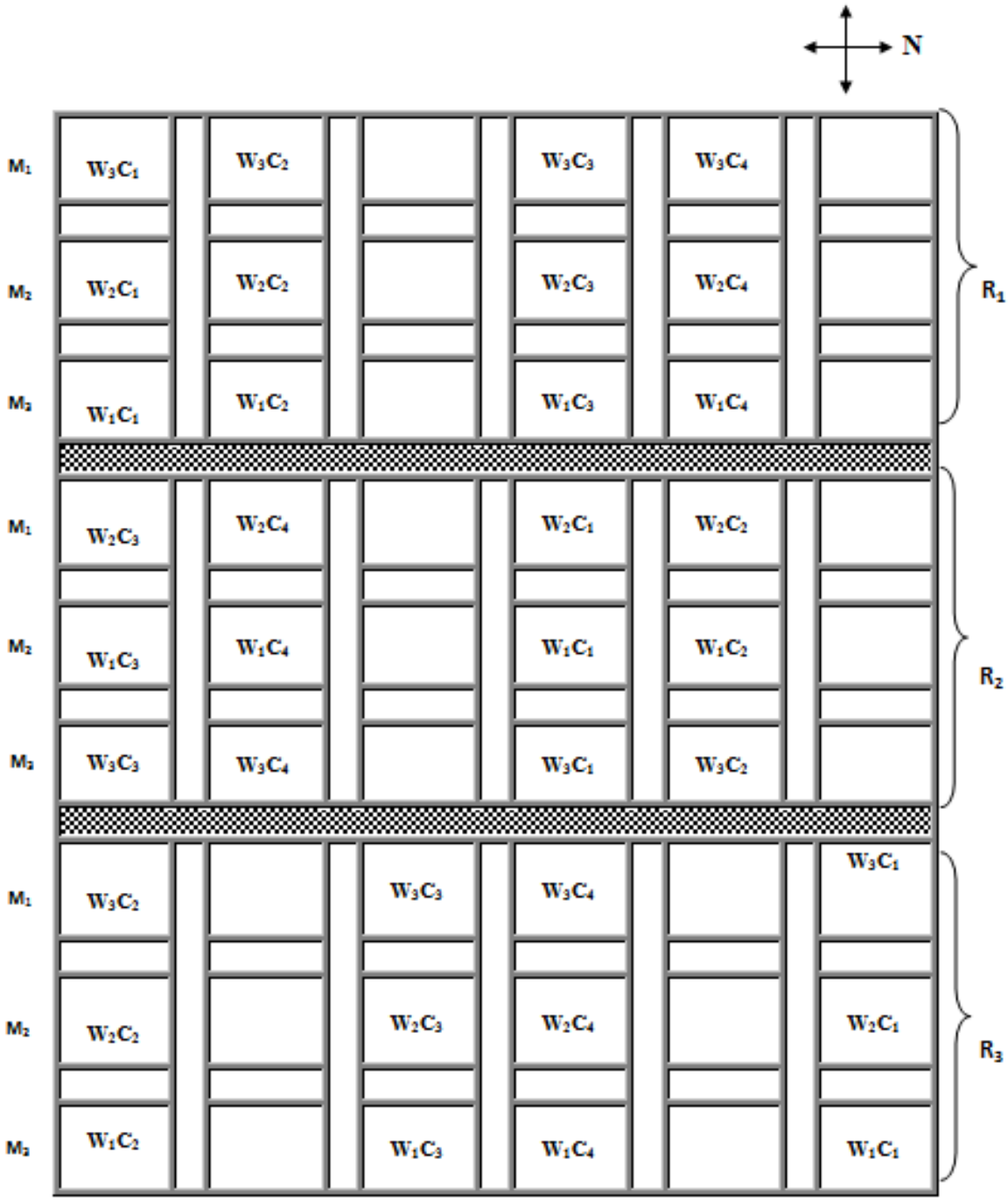
of water stable aggregates). After drying in shade, they were broken by dropping from a fixed height and by gently crumbling the soil, only aggregates of size between 5-8 mm size were used (i.e., those which were retained over 5 mm sieve). Surface soil core samples were drawn from all plots for determination of surface soil bulk density after the harvest of rice crop. The soil samples collected were subjected to physical and chemical analysis for various parameters using standard procedures as described in table 3.2.

3.3 Crop growth and yield studies

Grain and straw yield were recorded from a net plot of 3 x 3.2 m^2 area after leaving the border rows to minimize the border effect and intra-plot effect. At physiological maturity, yield related parameter like rice crop canopy height (cm), no. of tillers m^{-2} and no. of panicles m^{-2} were determined. The harvested crop was threshed manually and the grain weight was recorded. Grain yield of each crop for each plot was worked out separately and converted into kg ha^{-1}. For nutrient uptake calculations in terms of N, P and K by the grains and straw of rice, plant samples were drawn from an area of 25 x 30 cm^2 from two sites in each plot. The grain and straw plant samples were washed with a mild detergent, rinsed with distilled water, air dried the samples on a clean surface at room temperature for at least 2-3 days in a dust-free atmosphere away from any kind of contaminants and then oven dried at 60°C for 48 hours.

3.4 In situ measurement of soil conditions

A cone penetrometer (Make: Daiki Rika Kogyo Co Ltd., Japan; Model: DIK-5532) was used for measurement of penetration resistance upto a depth of 60 cm within the profile during May 2016, i.e. after the completion of two cropping cycles and before the beginning of the third cropping cycle (i.e., before rice cultivation and after rice harvesting) at three locations in each plot. Another measurement of soil profile



C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation in post-rice crops
Plot size: 4.0×4.2 m^2

Figure 3.2: Layout of the experimental field at BAC farm, Sabour showing the placement of various treatments.

Table 3.2 List of soil physico-chemical parameters measured along with the respective methods used.

Sl. No.	Parameter	Method	Reference
1	Bulk Density	Core sampler	Blake, 1965
2	Maximum Water Holding Capacity	Keen Box	Keen and Raczkowski, 1921.
3	Wet Aggregate Stability	Wet sieving	Yoder, 1936
4	pH	Soil water suspension	Peech, 1965
5	EC	Soil water suspension	Jackson, 1973
6	Soil organic carbon	Wet digestion	Allison, 1965
7	Available N	Alkaline potassium permanganate	Subbiah & Asija, 1956
8	Available P	Colorimetric method	Olsen *et al*., 1954
9	Available K	Neutral normal ammonium acetate	Jackson, 1973

Table 3.3 Methods used for nutrient analysis of plant samples.

Sl. No.	Parameters	Method	Reference
1	Total N	Micro Kjeldahl	Davidescu and Davidescu (1972)
2	Total P	Vanadomolybdate Phosphoric acid method	Koenig and Johnson (1942)
3	Total K	Wet digestion method	Chapman and Pratt (1961)

penetration resistance up to a depth of 90 cm was made in November, 2016 just before the harvest of the rice crop from three locations in each plot (Davidson, 1965). Steady state infiltration rate was measured using double ring infiltrometer at one location in only one replication to have an idea of the infiltration rate. Replicated measurements of infiltration rate were not possible because of the lesser duration of fallow period between the harvest of rice and sowing of post rice crops. The dry weights of both straw and grain were determined. The grain and straw samples were then ground in a Wiley mill grinder and digested to determine the N, P and K content using standard plant sample analysis procedures listed in table 3.3 .

3.5 Efficiency indices of various nutrients

The use efficiency of the primary nutrients was estimated using the indices such as internal nutrient use efficiency, partial factor productivity of applied nutrients, nutrient harvest index, and physiological nutrient use efficiency. These were calculated based on the following formulae:

(1) Internal nutrient use efficiency

$$\textbf{INUE (kg/kg)} = \frac{\textbf{Grain yield}}{\textbf{Total nutrient uptake}}$$

(2) Partial factor productivity of applied nutrient (PFPN)

$$\textbf{PFPN (kg/kg)} = \frac{\textbf{Grain yield}}{\textbf{Quantity of nutrient applied}}$$

(3) Nutrient harvest index (NHI)

$$\textbf{NHI (\%)} = \frac{\textbf{Grain nutrient uptake}}{\textbf{Total nutrient uptake}}$$

(4) Physiological nutrient use efficiency (PNUE)

$$\textbf{PNUE (kg/kg)} = \frac{\textbf{Dry matter production}}{\textbf{Total nutrient uptake}}$$

3.6 Statistical analysis

The data for various parameters was analyzed for variance as for a split plot design considering the three fertigation regimes as the main plot treatments and four of the rice based cropping systems as sub plot treatments.

Result

RESULTS

The effect of various fertigation regimes and cropping systems imposed since *kharif* 2014 are likely to have their impact on crop growth characteristics as well as the soil physical conditions and nutrient availability in the soils. These effects, being reported in the present study during the third rice crop in the system during *kharif* 2016, as measured and quantified from field observations of crop characteristics, in situ measurements in the soil system as well as ex-ante and ex-post analysis of soil samples is described in the following sections.

4.1 Rice growth and yield parameters as influenced by various fertigation regimes and cropping systems

The data regarding the effect of fertigation and cropping systems on grain and straw yield of rice along with harvest indices is presented in table 4.1. The data shows that the rice grain yield was significantly greater under the W_2 and W_3 fertigation regime after harvesting of rice. There was no significant effect of cropping systems on rice grain yield. No significant effect of fertigation and cropping systems was observed on the straw yield of rice. The effect of various treatments on rice straw yield was found to be non-significant. Various rice-based cropping systems and fertigation regimes had no significant effect on harvest index of the rice crop during 2016.

The data regarding rice canopy height, no. of tillers m^{-2} and no. of panicles m^{-2} as affected by various fertigation regimes and cropping systems is presented in table 4.2. No significant effect of fertigation and cropping systems on plant canopy height, no. of tillers m^{-2} and no. of panicles m^{-2} was observed during the study.

4.2 In situ measurements in the soil system

Table 4.1 Effect of fertigation regimes and rice based cropping systems on rice paddy yield (kg ha^{-1}).

	Straw yield (kg ha^{-1})				Grain yield (kg ha^{-1})				Harvest Index			
Treatments	W_1	W_2	W_3	Mean	W_1	W_2	W_3	Mean	W_1	W_2	W_3	Mean
C_1	3579.2	4957.8	5153.8	**4563.6**	3106.6	3655.3	4285.1	**3682.3**	0.47	0.42	0.45	**0.45**
C_2	4077.1	4708.3	4934.0	**4573.2**	3041.1	3381.5	3409.3	**3277.3**	0.43	0.42	0.41	**0.42**
C_3	3812.6	4739.4	5454.2	**4668.7**	2883.3	3325.5	3386.7	**3198.5**	0.43	0.41	0.38	**0.41**
C_4	3773.6	4708.3	4766.0	**4416.0**	2706.9	3398.6	3514.6	**3206.7**	0.42	0.42	0.43	**0.42**
Mean	**3810.6**	**4778.5**	**5077.0**		**2934.5**	**3440.2**	**3648.9**		**0.44**	**0.42**	**0.42**	
LSD(0.05)W:C::WxC	NS:NS::NS				470.18:NS::NS				NS:NS::NS			

C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crops

Table 4.2 Effect of fertigation regimes and rice based cropping systems on rice crop canopy height (cm), no. of tillers m^{-2} and no. of panicles m^{-2} during 2016.

	Canopy height (cm)				No of tillers m^{-2}				No of panicles m^{-2}			
Treatment	W_1	W_2	W_3	Mean	W_1	W_2	W_3	Mean	W_1	W_2	W_3	Mean
C_1	107.9	111.9	107.2	**109.0**	262.0	290.0	271.3	**274.4**	257.0	279.7	262.0	**266.2**
C_2	107.4	111.1	108.5	**109.0**	285.7	256.7	234.0	**258.8**	278.7	248.7	223.0	**250.1**
C_3	113.0	108.1	109.8	**110.3**	225.7	288.3	278.3	**264.1**	220.0	280.7	269.7	**256.8**
C_4	111.8	112.2	107.8	**110.6**	243.0	286.0	245.3	**258.1**	233.7	277.7	237.3	**249.6**
Mean	**110.0**	**110.8**	**108.3**		**254.1**	**280.3**	**257.3**		**247.3**	**271.7**	**248.0**	
LSD(0.05)W:C::WxC	NS:NS::NS				NS:NS::NS				NS:NS::NS			

C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crops

4.2.1 Effect of different fertigation regimes and rice based cropping systems on soil profile penetration resistance

The soil profile penetration resistance across various fertigation regimes measured before rice crop establishment and just before the harvest of rice crop and plotted against the respective depths of measurement for comparison using a polynomial trend line of order 3 is shown in figures 4.1 and 4.2. Figure 4.1 demonstrates the distinct influence of various fertigation regimes on the soil profile penetration resistance in field measurements before the rice crop establishment. The three fertigation regimes demonstrate distinct trends of variation in penetration resistance with depth in the profile. W_1 fertigation regime exhibits a sharp increase in penetration resistance to a depth of about 20 cm after which there is an equally sharp decreasing trend. W_2 fertigation regimes exhibits a rather gentle increase in penetration resistance but this increasing trend is seen to a greater depth in the profile after which there is a gentle decreasing trend of penetration resistance. In W_3 fertigation regime, the initial increasing trend of penetration resistance with depth is at a still lower rate but persists to still greater depths before decreasing again. Figure 4.2 demonstrates that there is no observable difference in terms of the influence of various fertigation regimes on soil profile penetration resistance in field measurements made just before the harvest of rice crop during November, 2016.

The soil profile penetration resistance across various rice based cropping systems measured before rice crop establishment and just before the harvest of rice crop and plotted against the respective depths of measurement for comparison using a polynomial trend line of order 3 is shown in figures 4.3 and 4.4. Figure 4.3 demonstrates the distinct influence of various rice based cropping systems on the soil profile penetration resistance in field measurements before the rice crop establishment. The four rice based cropping systems demonstrate distinct trends of variation

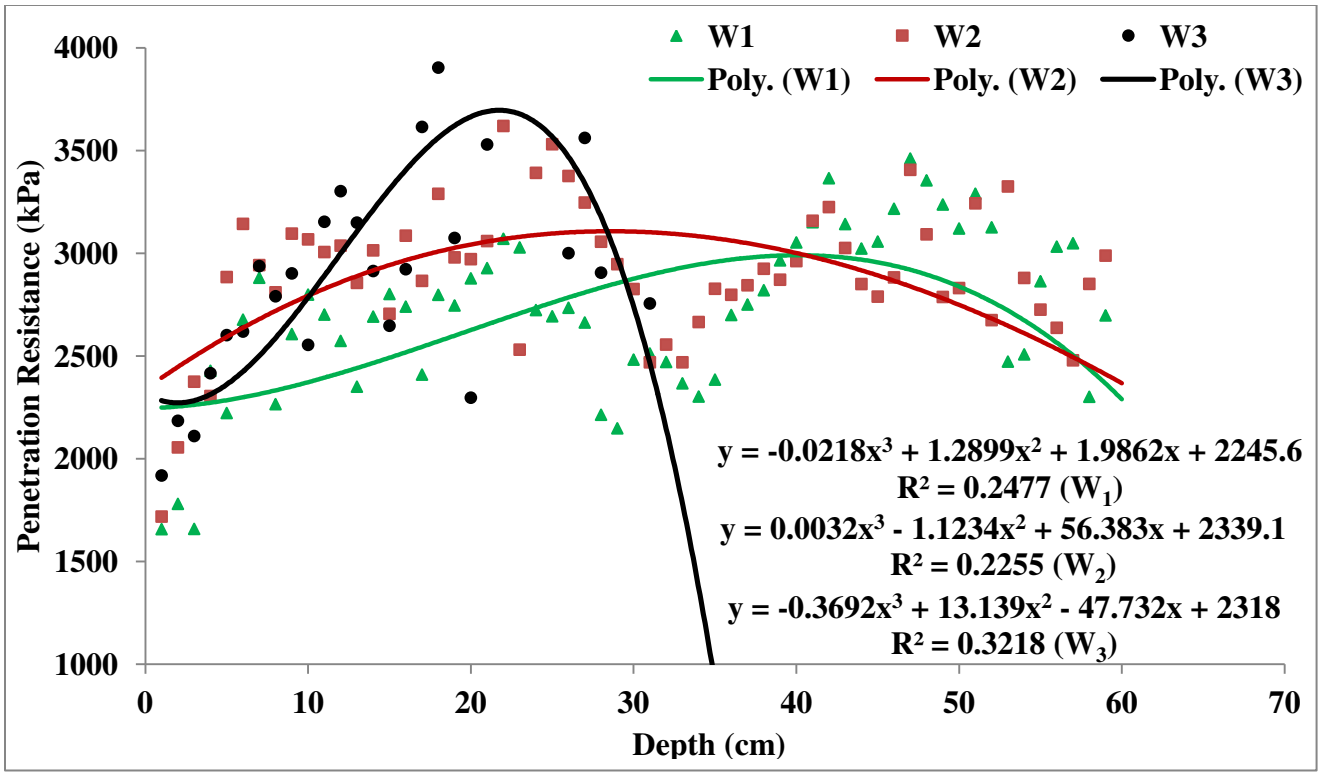


Figure 4.1 Effect of different fertigation regimes on soil profile penetration resistance in rice based cropping systems after two cropping cycles before the third rice crop establishment in May, 2016.

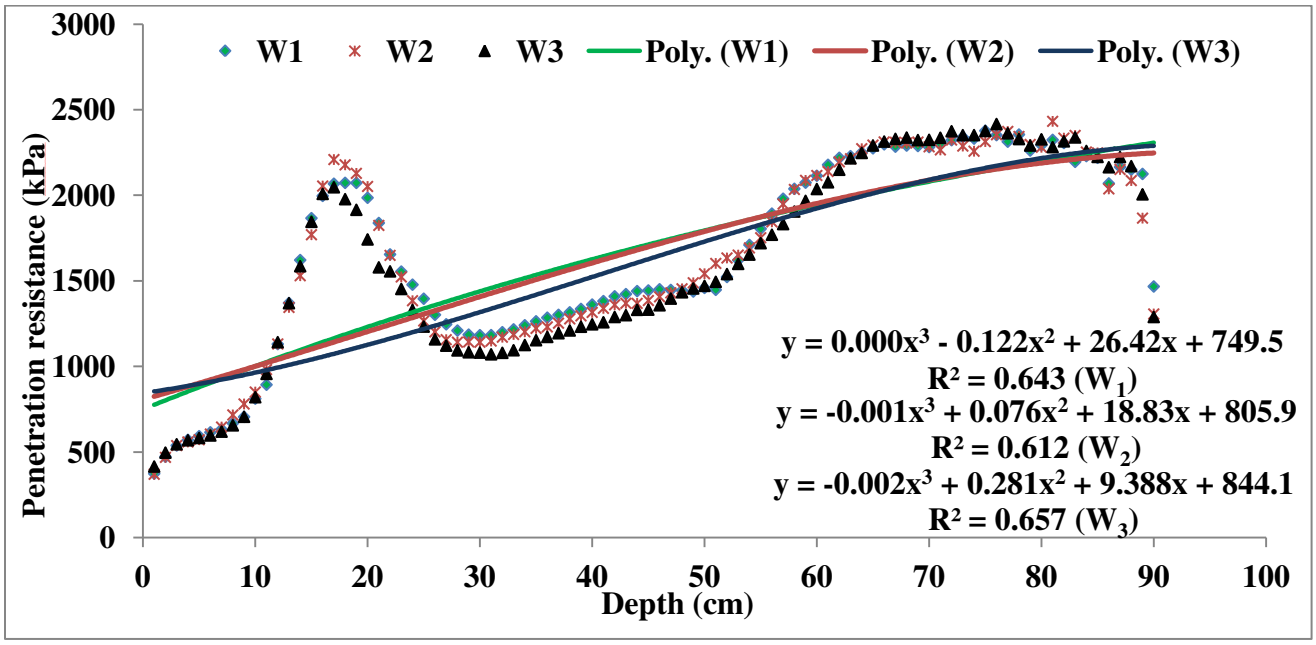


Figure 4.2 Effect of different fertigation regimes on soil profile penetration resistance in rice based cropping systems measured just before the harvest of the third rice crop in the system during November, 2016.

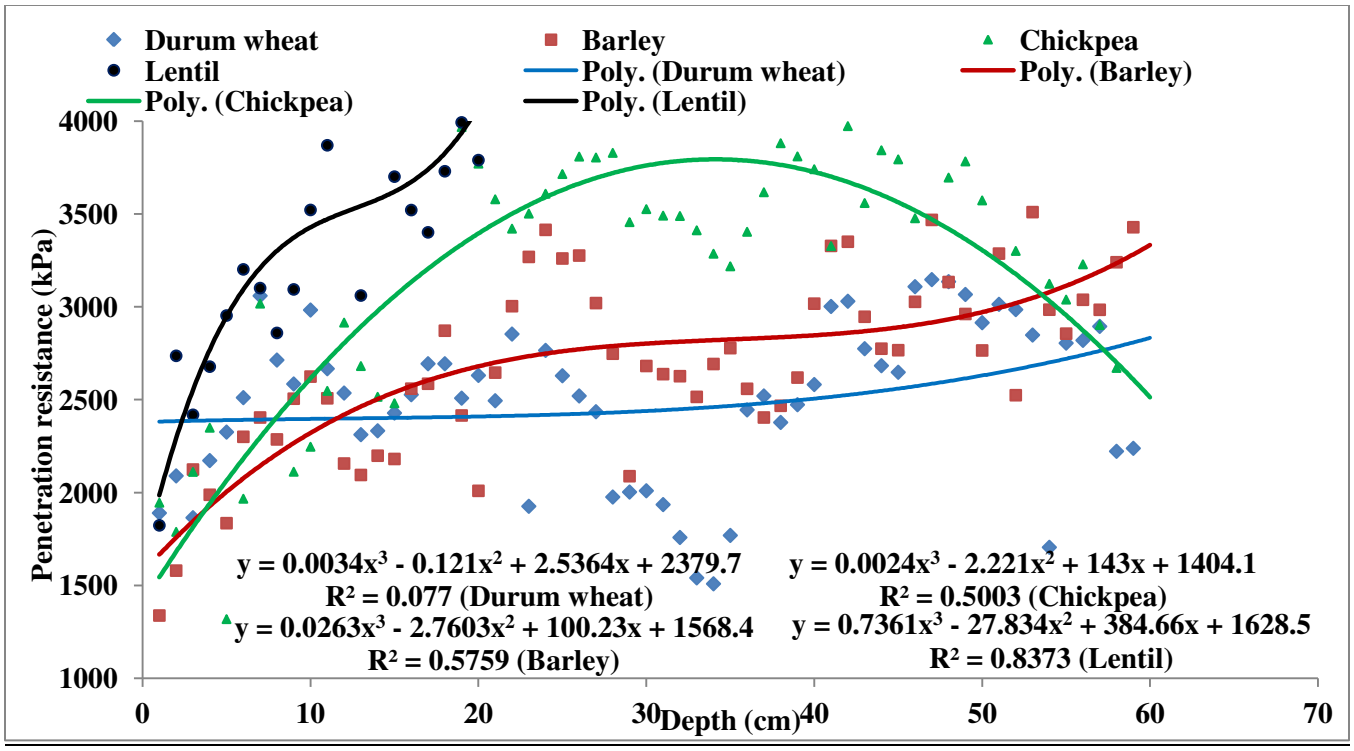


Figure 4.3 Effect of various rice based cropping systems on soil profile penetration resistance after two cropping cycles before the third rice crop establishment during May, 2016.

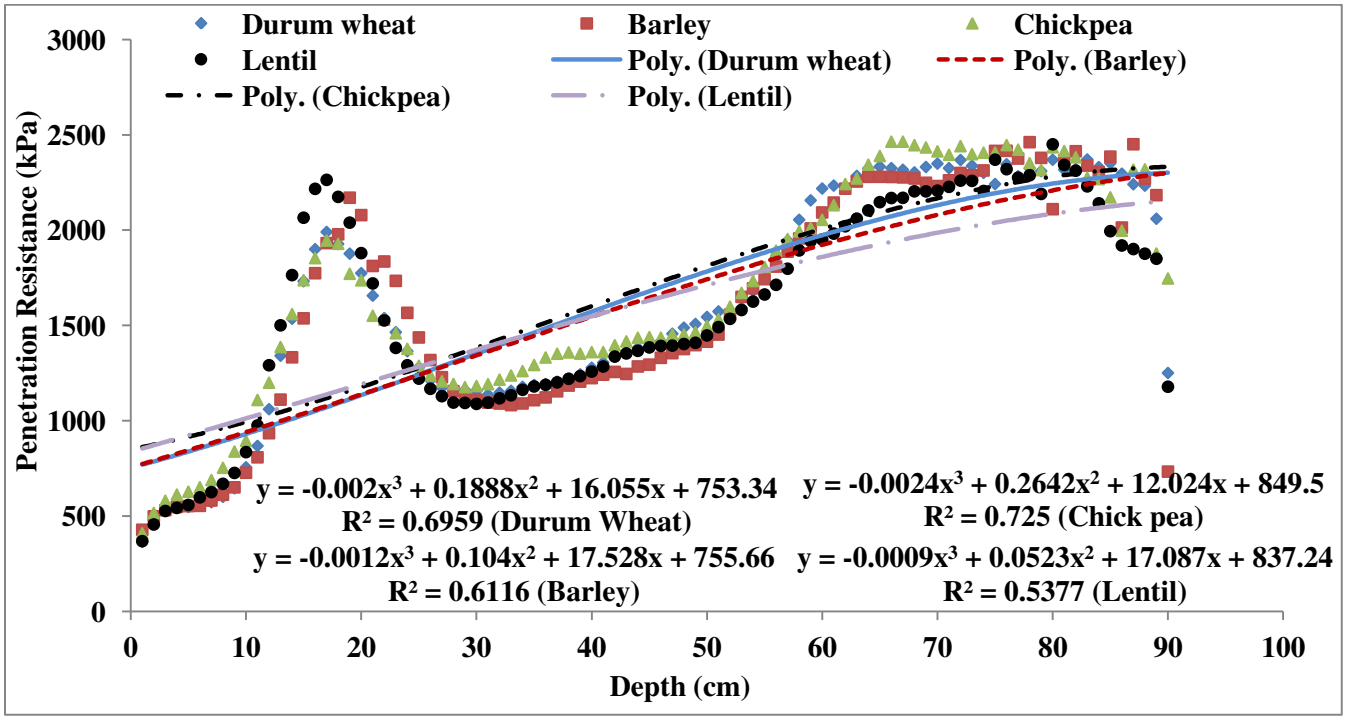


Figure 4.4 Effect of various rice based cropping systems on soil profile penetration resistance measured just before the harvest of the third rice crop in the system during November, 2016.

in penetration resistance with depth in the profile. In rice lentil cropping system, the penetration resistance appears to be higher at all depths in comparison to other cropping systems. The penetration resistance measured at the surface averaged at about 1700 kPa but steeply increased to a level of about 4000 kPa at a depth of 20-25 cm beyond which it was not possible to push the cone into the soil. In rice-chickpea cropping system, the PR was lower than rice-lentil cropping system but higher than rice-durum wheat and rice-barley cropping systems. The penetration resistance in rice-durum wheat plots was found to exhibit wide fluctuations leading to non-significant polynomial trend-line of order 3 when penetration resistance was plotted against the respective depths. Figure 4.4 demonstrates that there is no observable difference in terms of the influence of various rice based cropping systems on soil profile penetration resistance in field measurements made just before the harvest of rice crop during November, 2016.

4.2.2 Effect of fertigation regimes and rice based cropping systems on steady state infiltration rate of soil

The un-replicated observations of steady state infiltration rate, presented in table 4.3 indicate that the infiltration rate was found to be lower in rice-legume cropping systems (both chickpea and lentil) in comparison to all cereal based cropping systems. The time series cumulative infiltration under various fertigation regimes and cropping systems measured after the harvest of the third rice crop in the system during November, 2016 have been shown in figures 4.5, 4.6 and 4.7. These curves show that there are heterogeneities in the system, which can better be characterized and described with greater confidence by replicated observations.

4.3 Effect of fertigation regimes and rice based cropping systems on soil physical properties

4.3.1 Effect of fertigation regimes and rice based cropping systems on soil bulk density

Table 4.3 Effect of fertigation regimes and rice based cropping systems on steady state infiltration rate (cm h^{-1}) (un-replicated measurements) during November, 2016.

Treatment	W_1	W_2	W_3	Mean
C_1	1.7	1.4	1.0	**1.4**
C_2	1.4	0.2	1.5	**1.0**
C_3	0.3	0.2	1.1	**0.5**
C_4	0.2	0.4	1.0	**0.5**
Mean	**0.9**	**0.6**	**1.2**	

C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crops

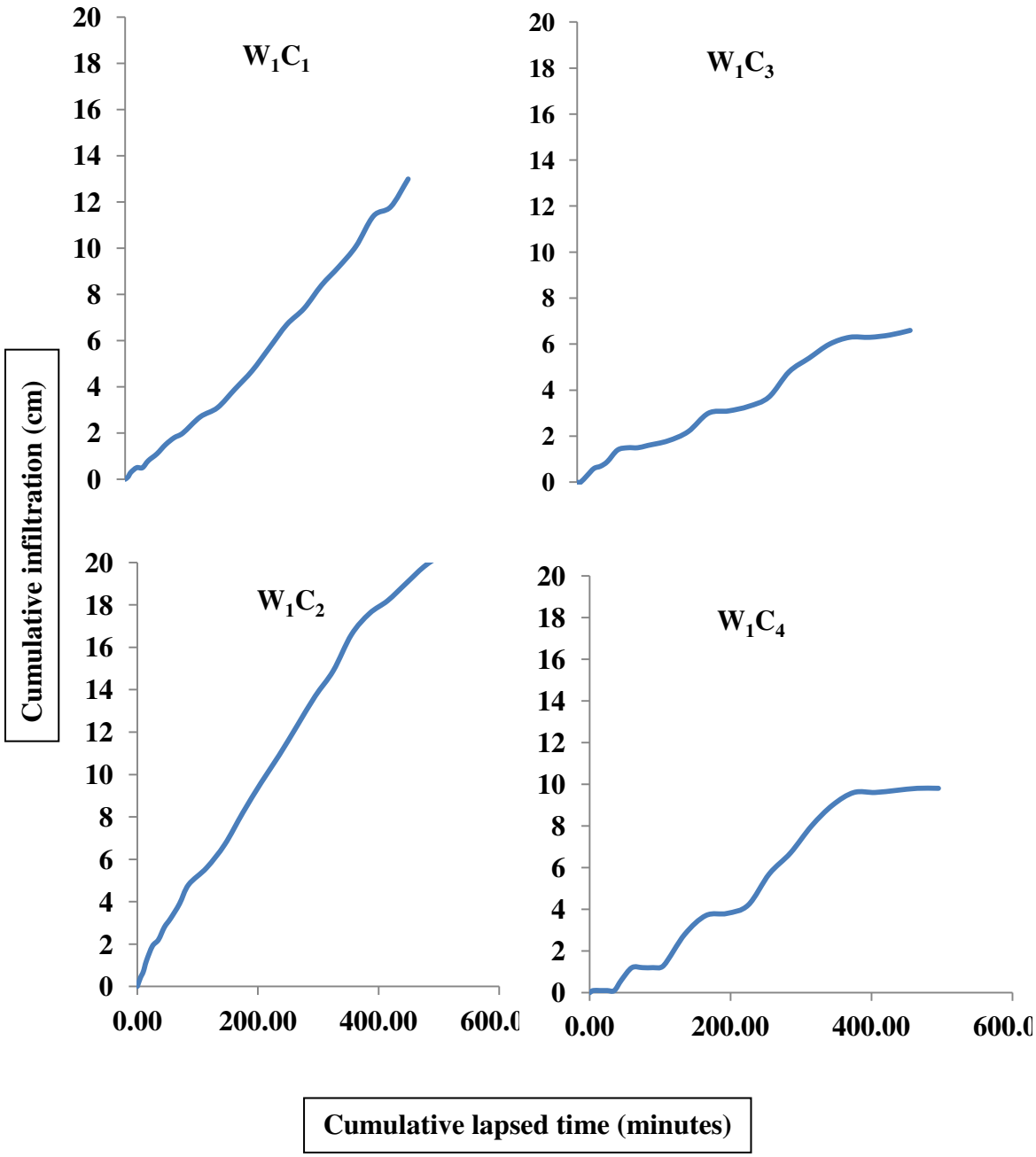


Figure 4.5 Effect of various rice based cropping systems under W_1 fertigation regime on time series cumulative infiltration measured after the harvest of the third rice crop in the system during November, 2016.

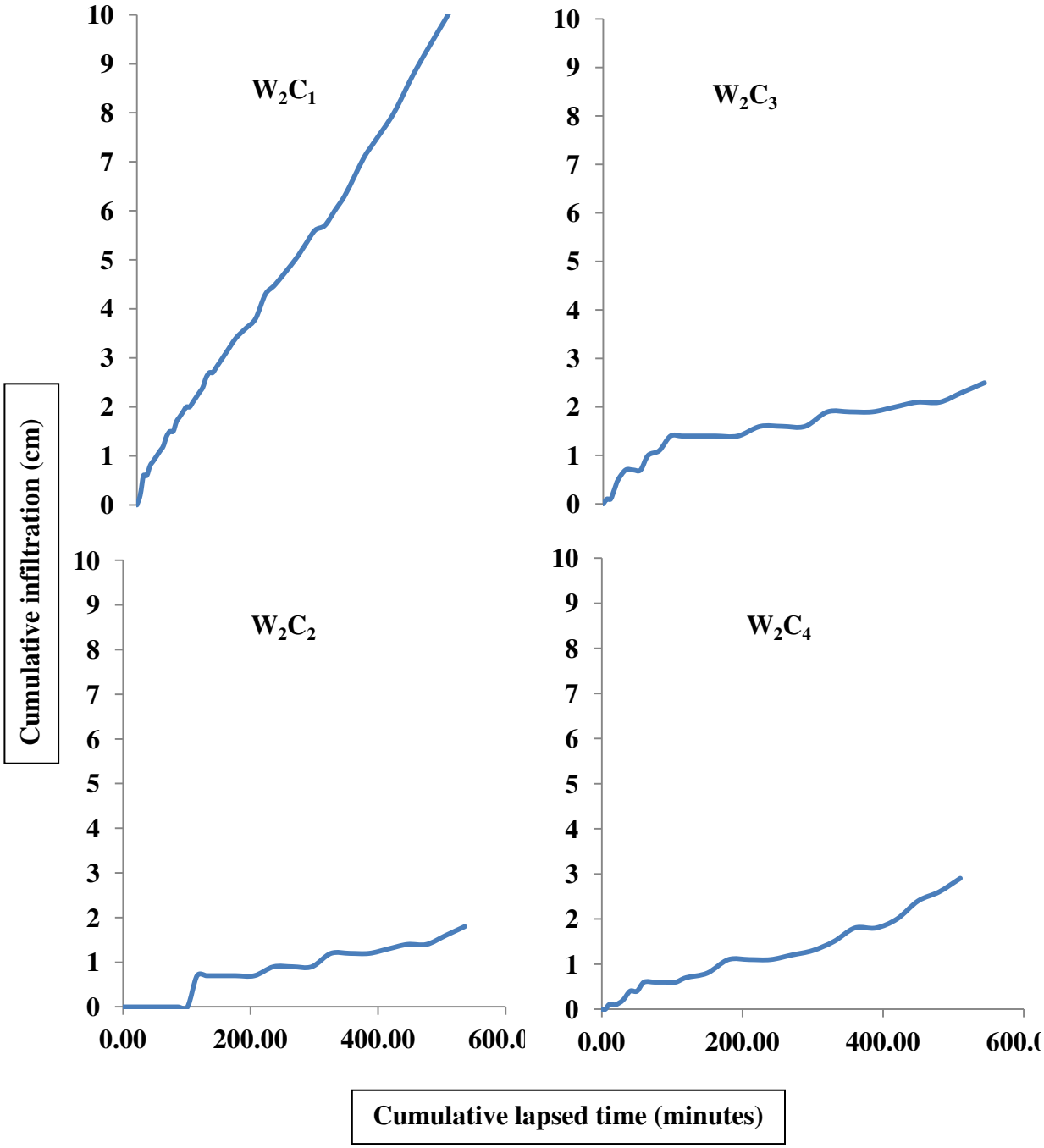


Figure 4.6 Effect of various rice based cropping systems under W_2 fertigation regime on time series cumulative infiltration measured after the harvest of the third rice crop in the system during November, 2016.

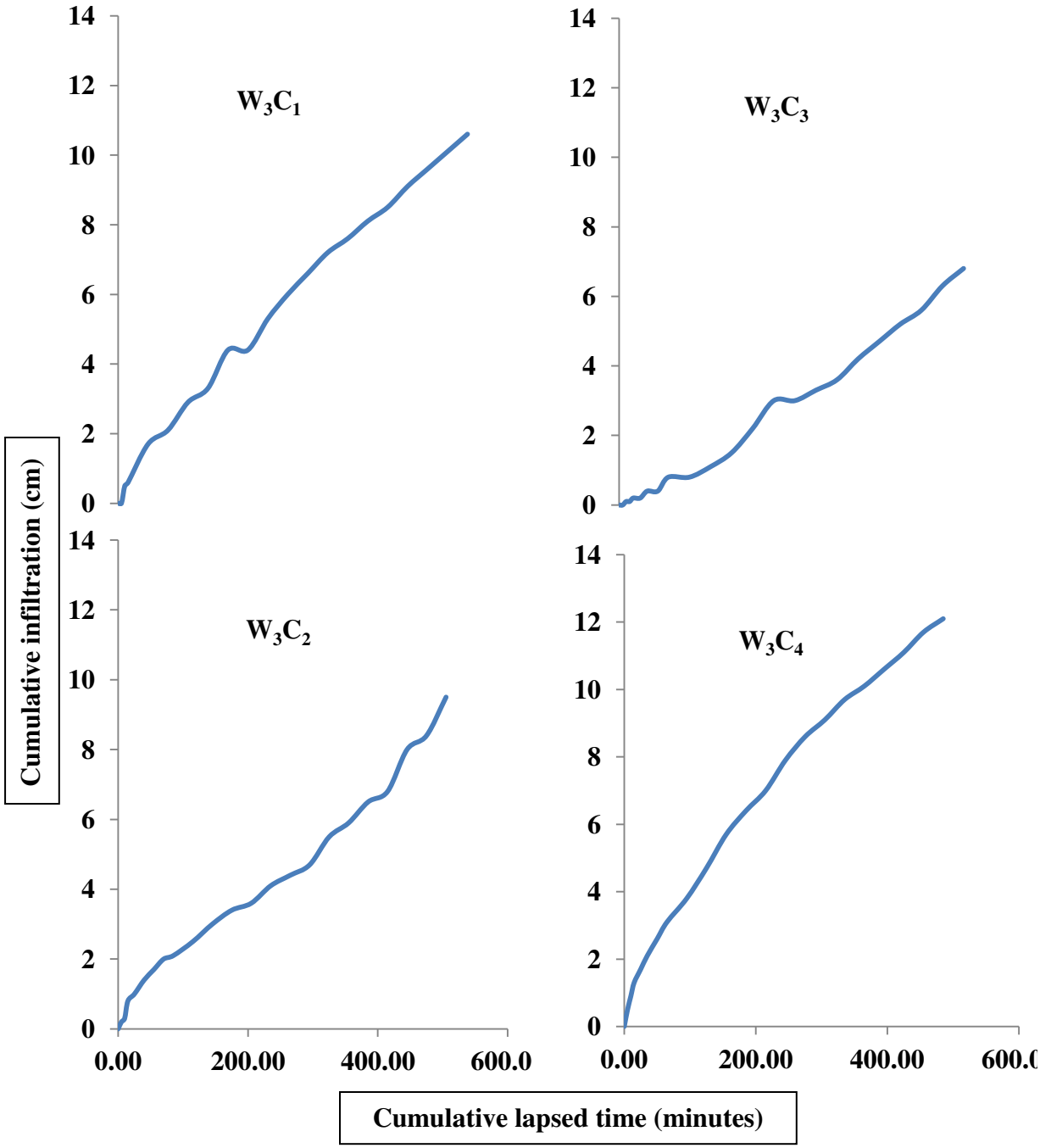


Figure 4.7 Effect of various rice based cropping systems under W_3 fertigation regime on time series cumulative infiltration measured after the harvest of the third rice crop in the system during November, 2016.

The data pertaining to the effect of fertigation regimes and rice based cropping systems on BD of surface soil after rice harvest measured from soil core samples after the harvest of the rice crops during November 2016 is presented in table 4.4. The data shows that there was no significant effect of various fertigation regimes and the studied cropping systems on bulk density of the surface soil as measured after the harvest of rice crop during November, 2016.

4.3.2 Effect of fertigation regimes and rice based cropping systems on maximum water holding capacity of soil

Table 4.5 shows the effect of fertigation regimes and rice based cropping systems on maximum water holding capacity of soil at various depths. The data shows that the maximum water holding capacity of surface soil after the harvest of *rabi* season crops in 2015-16 was significantly greater under W_2 (44.12 %) and W_3 (44.89 %) fertigation regimes in comparison to that under W_1 (42.12 %) fertigation regime. However, this effect did not persist till the harvest of the next rice crop in November 2016. No significant effects of various fertigation regimes on maximum water holding capacity of soil at other depths and times was found. Similarly, no significant effect of various cropping systems was observed in the maximum water holding capacity of soil at various depths during the study.

4.3.3 Effect of various fertigation regimes and rice based cropping systems on wet aggregate stability of surface soil

The data in Table 4.6 shows the effect of various fertigation regimes and rice based cropping systems on wet aggregate stability of surface soil measured in terms of mean weight diameter and geometric mean diameter of water stable aggregates before and after the third rice crop in rice based cropping systems involving zero tilled establishment of direct seeded rice and *rabi*

Table 4.4 Effect of fertigation regimes and rice based cropping systems on bulk density (Mg m^{-3}) of surface soil after the harvest of a zero tilled direct seeded rice crop during November 2016.

Treatment	W_1	W_2	W_3	Mean
C_1	1.52	1.52	1.57	**1.54**
C_2	1.52	1.51	1.51	**1.51**
C_3	1.52	1.53	1.55	**1.53**
C_4	1.54	1.52	1.55	**1.53**
Mean	**1.53**	**1.52**	**1.54**	
LSD(0.05)W:C::WxC		NS:NS::NS		

C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crops

Table 4.5 Effect of fertigation regimes and rice based cropping systems on maximum water holding capacity of soil (%) at various depths

Treatment	W_1	W_2	W_3	Mean	W_1	W_2	W_3	Mean	W_1	W_2	W_3	Mean
	0-15 cm				15-30 cm				30-45 cm			
	Before rice crop establishment in May, 2016											
C_1	40.69	44.67	44.19	**43.18**	41.99	41.90	45.46	**43.12**	40.57	42.62	44.38	**42.52**
C_2	42.24	45.12	46.19	**44.52**	40.84	41.82	44.54	**42.40**	44.53	44.40	43.28	**44.07**
C_3	43.24	42.50	44.19	**43.31**	43.97	43.32	44.18	**42.82**	43.29	44.88	47.18	**45.11**
C_4	42.61	44.19	45.00	**43.94**	41.92	42.44	44.90	**43.09**	42.90	45.28	45.88	**44.69**
Mean	**42.12**	**44.12**	**44.89**		**42.18**	**42.37**	**44.77**		**42.82**	**44.30**	**45.18**	
LSD(0.05)W:C::WxC	1.73:NS::NS				NS:NS::NS				NS:NS::NS			
Treatment	After harvesting of rice crop in November, 2016											
C_1	49.47	48.09	45.61	**47.72**	46.16	46.86	46.16	**46.39**	45.03	46.33	42.51	**44.62**
C_2	45.75	47.02	45.23	**46.00**	43.60	46.54	46.41	**45.51**	45.92	46.63	46.55	**46.36**
C_3	45.87	47.62	46.31	**46.60**	46.85	47.56	43.13	**45.85**	44.22	46.70	44.33	**45.08**
C_4	46.02	47.68	46.34	**46.68**	45.00	44.53	44.06	**44.53**	43.12	42.47	41.60	**42.39**
Mean	**46.78**	**47.60**	**45.87**		**45.40**	**46.37**	**44.94**		**44.57**	**45.53**	**43.75**	
LSD(0.05)W:C::WxC	NS:NS::NS				NS:NS::NS				NS:NS::NS			

C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crops

Table 4.6 Effect of fertigation regimes and rice based cropping systems on wet aggregate stability of surface soil

Treatments	MWD (mm)				GMD (mm)			
	W_1	W_2	W_3	Mean	W_1	W_2	W_3	Mean
	Before rice crop establishment in May, 2016							
C_1	0.32	0.28	0.31	**0.30**	0.36	0.37	0.38	**0.37**
C_2	0.27	0.35	0.23	**0.29**	0.37	0.41	0.36	**0.38**
C_3	0.31	0.25	0.26	**0.27**	0.37	0.37	0.37	**0.37**
C_4	0.31	0.18	0.36	**0.28**	0.37	0.34	0.37	**0.36**
Mean	**0.30**	**0.27**	**0.29**		**0.37**	**0.37**	**0.37**	
LSD(0.05)W:C::WxC	NS:NS::NS				NS:NS::NS			
Treatments	After harvesting of rice crop in November, 2016							
C_1	0.68	1.07	1.07	**0.94**	0.43	0.47	0.47	**0.46**
C_2	0.74	1.25	0.98	**0.99**	0.42	0.51	0.46	**0.46**
C_3	1.07	1.37	1.58	**1.34**	0.46	0.51	0.55	**0.51**
C_4	0.58	1.10	1.24	**0.97**	0.45	0.47	0.49	**0.47**
Mean	**0.77**	**1.20**	**1.22**		**0.44**	**0.49**	**0.49**	
LSD(0.05)W:C::WxC	0.34:NS::NS				0.034:NS::NS			

C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crops

season crops. There was no significant effect of any treatment on MWD and GMD after the harvest of *rabi* season crops in the second year measured during the month of May 2016. However, the measurements of water stable aggregates after the harvest of third rice crop in the rotation during November, 2016 revealed that these parameters were significantly greater under W_2 (1.20 mm and 0.49 mm respectively) and W_3 (1.22 mm and 0.49 mm, respectively) fertigation regimes. No significant interaction of various fertigation regimes was found with the cropping systems.

4.4 Effect of fertigation regimes and rice based cropping systems on organic carbon and nutrient availability

4.4.1. Effect of fertigation regimes and rice based cropping systems on wet oxidizable organic carbon in soil at various depths

The data regarding the effect of rice based cropping systems and fertigation regimes on wet oxidizable organic carbon of soil at various depths before rice crop establishment and after rice harvest is presented in table 4.7. No significant effect of various fertigation regimes on organic carbon content in the soil at surface, 15-30 cm depth and at 30-45 cm depth was observed before rice crop establishment as well as after the harvest of rice crop during 2016. The data shows that the organic carbon content of the surface soil was significantly lower in the rice-chickpea cropping system in comparison to the rice-durum wheat and rice-barley cropping system before the establishment of rice crop during 2016. At 15-30 cm soil depth, significantly lower organic carbon content was found in rice-chickpea cropping system in comparison to other three systems before the establishment of rice crop. At the depth of 30-45 cm, before rice crop establishment, wet

Table 4.7 Effect of fertigation regimes and rice based cropping systems on soil organic carbon content (%) at various depths

Treatment	W_1	W_2	W_3	Mean	W_1	W_2	W_3	Mean	W_1	W_2	W_3	Mean
	0-15 cm				15-30 cm				30-45 cm			
	Before rice crop establishment in May, 2016											
C_1	0.50	0.50	0.47	**0.49**	0.25	0.28	0.33	**0.29**	0.26	0.19	0.24	**0.23**
C_2	0.53	0.50	0.48	**0.50**	0.33	0.30	0.33	**0.32**	0.23	0.16	0.25	**0.21**
C_3	0.45	0.42	0.42	**0.43**	0.23	0.30	0.23	**0.25**	0.21	0.22	0.25	**0.23**
C_4	0.44	0.48	0.48	**0.47**	0.34	0.32	0.27	**0.31**	0.28	0.30	0.23	**0.27**
Mean	**0.48**	**0.48**	**0.46**		**0.29**	**0.30**	**0.29**		**0.24**	**0.22**	**0.24**	
LSD(0.05)W:C::WXC	NS:0.04::NS				NS:0.02::0.03				NS:0.03::0.04			
Treatment	After harvesting of rice crop in November, 2016											
C_1	0.43	0.45	0.48	**0.45**	0.33	0.24	0.32	**0.30**	0.29	0.30	0.22	**0.27**
C_2	0.43	0.39	0.46	**0.43**	0.33	0.27	0.31	**0.30**	0.23	0.25	0.29	**0.26**
C_3	0.39	0.43	0.41	**0.41**	0.30	0.32	0.27	**0.30**	0.25	0.28	0.24	**0.26**
C_4	0.36	0.41	0.50	**0.42**	0.26	0.33	0.26	**0.28**	0.22	0.28	0.24	**0.25**
Mean	**0.40**	**0.42**	**0.46**		**0.31**	**0.29**	**0.29**		**0.25**	**0.28**	**0.25**	
LSD(0.05)W:C::WXC	NS:NS::NS				NS:NS::0.04				NS:NS::0.05			

C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crops

oxidizable soil organic carbon content was significantly greater in rice-lentil cropping system in comparison to other cropping systems. Various fertigation regimes and cropping systems were found to be significantly interacting to influence the soil organic carbon content both, before rice crop establishment as well as after the harvest of the rice crop at the depth of 15-30 cm as well as 30-45 cm.

4.4.2. Effect of fertigation regimes and rice based cropping systems on nitrogen availability in soil

The data regarding the effect of fertigation regimes and rice based cropping systems on soil available nitrogen at various depths before rice crop establishment and after rice harvest is presented in table 4.8. The data shows that the effect of various fertigation regimes on available nitrogen in the soil surface layer was non-significant after the harvest of *rabi* season crops in May 2016 as well as after the harvest of the rice crop in November, 2016. At lower depths, *i.e*., at 15-30 cm and 30-45 cm soil depths, more nitrogen was available in treatments receiving less irrigation through fertigation during the *rabi* season. However, this trend did not persist after the harvest of the rice crop. The data shows that before the rice crop establishment, there was no significant difference in the available nitrogen content across various cropping systems at any of the depths. However, after the harvest of the rice crop, the available nitrogen content in the soil surface was minimum in rice-chickpea cropping system followed by that in the rice durum wheat cropping system and maximum in rice-barley and rice-lentil cropping system, both of which were statistically similar. The available nitrogen content in the 15-30 cm and 30-45 cm soil layers was

Table 4.8.Effect of fertigation regimes and rice based cropping systems on available nitrogen (kg ha^{-1}) of soil at various depths

Treatment	W_1	W_2	W_3	Mean	W_1	W_2	W_3	Mean	W_1	W_2	W_3	Mean
	0-15 cm				15-30 cm				30-45 cm			
	Before rice crop establishment in May, 2016											
C_1	142.8	147.0	132.3	**140.7**	144.9	144.9	123.9	**137.9**	147.0	132.3	123.9	**134.4**
C_2	144.9	165.9	144.9	**151.9**	140.7	163.8	128.1	**144.2**	130.2	138.6	123.9	**130.9**
C_3	153.3	153.3	132.3	**146.3**	151.2	136.5	115.5	**134.4**	151.2	134.4	109.2	**131.6**
C_4	153.3	155.4	130.2	**146.3**	138.6	134.4	136.5	**136.5**	144.9	132.3	130.2	**135.8**
Mean	**148.6**	**155.4**	**134.9**		**143.9**	**144.9**	**126.0**		**143.3**	**134.4**	**121.8**	
LSD(0.05)W:C::WxC	NS:NS::NS				10.41:NS::17.21				6.65:NS::NS			
Treatment	After harvesting of rice crop in November, 2016											
C_1	136.5	126.0	142.8	**135.1**	140.7	128.1	142.8	**137.2**	128.1	121.8	140.7	**130.2**
C_2	140.7	151.2	147.0	**146.3**	121.8	147.0	151.2	**140.0**	140.7	138.6	136.5	**138.6**
C_3	134.4	119.7	123.9	**126.0**	128.1	123.9	117.6	**123.0**	123.9	117.6	113.4	**118.3**
C_4	155.4	142.8	130.2	**142.8**	138.6	126.0	130.2	**131.6**	138.6	121.8	140.7	**133.7**
Mean	**141.8**	**134.93**	**136.0**		**132.3**	**131.1**	**135.5**		**132.8**	**125.0**	**132.8**	
LSD(0.05)W:C::WxC	NS:6.78::11.74				NS:6.77::11.72				NS:6.5::11.30			

C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crops

also significantly lower in rice-chickpea cropping system in comparison to other cropping systems. Before rice crop establishment, cropping systems and fertigation regimes were found to interact significantly to create statistically significant differences in available nitrogen in 15-30 cm soil layer among various treatment combinations. After the harvest of rice crop, the interactions of fertigation regimes and cropping systems created statistically significant differences in available nitrogen content among various treatment combinations in the soil surface layer as well as in the 30-45 cm soil layer. In general, the available nitrogen content was lowest in rice chickpea cropping system and that too at higher levels of fertigation.

4.4.3. Effect of fertigation regimes and rice based cropping systems on phosphorus availability in soil

The data regarding the effect of various fertigation regimes and rice based cropping systems on available phosphorus content of soil at various depths before rice crop establishment and after rice harvest is presented in table 4.9. Both before rice crop establishment as well as after the harvest of the rice crop, no significant effect of any fertigation regime was observed in terms of P availability in the surface as well as the sub-surface soil layer. At the depth of 30-45 cm, soil available P was significantly greater in W_3 in comparison to W_2 and W_1 and also in W_2 in comparison to W_1 before the rice crop establishment. After the harvest of rice crop, soil available P was still significantly greater in W_3 in comparison to W_2 and W_1, but W_2 and W_1 were statistically at par with each other. Before rice crop establishment, the average P availability was significantly higher in rice lentil cropping system than in rice chickpea cropping system, both of which had significantly higher P availability than rice-durum wheat and rice-barley cropping systems in the surface soil and at the depth of 15-30 cm. At the same time, at the depth of 30-45 cm, rice-barley cropping system exhibited statistically lower availability of P in comparison to other cropping

Table 4.9 Effect of fertigation regimes and rice based cropping systems on available phosphorus (P_2O_5, kg ha^{-1}) in soil at various depths

Treatment	W_1	W_2	W_3	Mean	W_1	W_2	W_3	Mean	W_1	W_2	W_3	Mean
	0-15 cm				15-30 cm				30-45 cm			
	Before rice crop establishment in May, 2016											
C_1	51.2	61.9	51.7	**54.9**	33.1	42.5	37.5	**37.7**	24.6	36.2	34.1	**31.6**
C_2	52.6	52.1	47.5	**50.7**	36.8	36.3	36.2	**36.4**	22.0	20.6	25.7	**22.8**
C_3	58.8	54.8	61.3	**58.3**	46.8	35.3	42.4	**41.5**	18.6	32.5	37.2	**29.4**
C_4	69.7	62.6	60.7	**64.3**	52.3	45.5	45.8	**47.8**	24.9	26.9	34.2	**28.7**
Mean	**58.1**	**57.8**	**55.3**		**42.2**	**39.9**	**40.4**		**22.5**	**29.0**	**32.8**	
LSD(0.05)W:C::WxC	NS:5.07::NS				NS:5.18::NS				3.85:3.54::6.14			
Treatment	After harvesting of rice crop in November, 2016											
C_1	53.6	64.0	42.8	**53.5**	42.2	42.2	46.8	**43.8**	31.4	35.7	34.7	**34.0**
C_2	59.5	58.0	43.4	**53.7**	52.2	33.2	57.2	**47.5**	26.9	20.4	41.9	**29.7**
C_3	56.0	52.3	52.0	**53.4**	37.9	67.1	45.2	**50.1**	28.3	47.3	44.9	**40.2**
C_4	51.4	61.1	57.4	**56.6**	53.5	40.5	64.4	**52.8**	45.6	34.0	59.5	**46.4**
Mean	**55.1**	**58.9**	**48.9**		**46.4**	**45.7**	**53.4**		**33.1**	**34.3**	**45.3**	
LSD(0.05)W:C::WxC	NS:NS::7.63				NS:NS::13.84				5.95:3.49::6.04			

C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crops

systems. After rice crop harvest, no significant effect of any cropping system on phosphorus availability of soil in the 15-30 cm soil layer was found. But after harvesting of rice crop at the depth of 30-45 cm, soil available P was significantly greater in rice lentil cropping system in comparison to the other three cropping systems. The interaction of fertigation regimes and cropping systems produced significant differences in P availability of various treatment combinations at a depth of 30-45 cm before the establishment of rice crop and at all depths after the harvest of rice crop.

4.4.4 Effect of fertigation regimes and rice based cropping systems on potassium availability in soil

The data regarding the effect of rice based cropping systems and fertigation regimes on available potash content of soil at various depths before rice crop establishment and after rice harvest is presented in table 4.10. The data shows that the ammonium acetate extractable K, expressed as potash, was statistically similar across various fertigation regimes and cropping systems before rice crop establishment as well as after the harvest of the rice crop at all depths except at the depth of 15-30 cm and 30-45 cm before rice crop establishment. Before rice crop establishment at the depth of 15-30 cm, the minimum potash availability was in W_1 followed by that in W_3 and maximum in W_2. At the depth of 30-45 cm soil before rice establishment, the availability of potash was significantly higher in W_2 and W_1 fertigation regimes and lowest in W_3 fertigation regime. The interaction of fertigation regimes and cropping systems resulted in significant differences in potash availability across various treatment combinations at the depth of 30-45 cm before the establishment of rice crop and at the depths of 0-15 cm and 30-45 cm after the harvest of rice crop.

4.5 Effect of fertigation regimes and rice based cropping systems on nutrient uptake by rice

Table 4.10 Effect of fertigation regimes and rice based cropping systems on available potash (K_2O, kg ha^{-1}) of soil at various depths.

Treatment	W_1	W_2	W_3	Mean	W_1	W_2	W_3	Mean	W_1	W_2	W_3	Mean
	0-15 cm				15-30 cm				30-45 cm			
	Before rice crop establishment in May, 2016											
C_1	88.70	117.82	94.98	**100.50**	96.32	116.03	115.58	**109.31**	117.82	158.14	120.51	**132.16**
C_2	97.66	100.35	90.50	**96.17**	115.58	111.55	95.42	**107.52**	147.39	116.48	107.97	**123.95**
C_3	92.29	91.84	99.50	**94.59**	86.02	107.07	108.86	**100.65**	110.66	133.95	127.23	**123.95**
C_4	86.02	103.49	92.29	**93.93**	108.86	120.96	110.66	**113.49**	137.98	139.78	113.34	**130.37**
Mean	**91.17**	**103.38**	**94.30**		**101.70**	**113.90**	**107.63**		**128.46**	**137.09**	**117.26**	
LSD(0.05)W:C::WxC	NS:NS::NS				5.79:NS::NS				11.32:NS::24.74			
Treatment	After harvesting of rice crop in November, 2016											
C_1	90.50	82.43	80.19	**84.37**	106.62	108.42	106.62	**107.22**	111.55	128.13	125.89	**121.86**
C_2	107.97	80.64	82.43	**90.35**	106.18	107.52	104.38	**106.03**	121.86	114.69	120.51	**119.02**
C_3	90.50	85.57	91.84	**89.30**	124.99	100.80	104.83	**110.21**	116.03	124.54	137.98	**126.19**
C_4	89.15	84.67	84.67	**86.17**	117.38	109.76	116.48	**114.54**	139.78	118.72	116.48	**124.99**
Mean	**94.53**	**83.33**	**84.78**		**113.79**	**106.62**	**108.08**		**122.30**	**121.52**	**125.22**	
LSD(0.05)W:C::WxC	NS:NS::10.51				NS:NS::NS				NS:NS::18.25			

C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crops

4.5.1 Effect of fertigation regimes and rice based cropping systems on nitrogen content and uptake by rice

The data regarding the effect of rice based cropping systems and fertigation regimes on nitrogen content (%) and uptake (kg ha^{-1}) in grains and straw is presented in table 4.11. No significant effect of fertigation regimes and cropping systems was found on nitrogen content and uptake by rice straw as well as on total N uptake. Rice-lentil cropping system resulted in significantly lower N uptake in rice grains than other cropping systems. Nitrogen uptake in rice grains was found to be significantly greater in rice-durum wheat system in comparison to other cropping systems. Among various fertigation regimes, W_2 and W_3 fertigation regimes resulted in significantly greater Nitrogen uptake in rice grains in comparison to W_1 fertigation regime. The interaction of fertigation regimes and cropping systems produced significant differences in N content of rice grains among various treatment combinations. However, the interaction effect of fertigation regimes and cropping system on N content in rice straw, N uptake by rice straw and grain and total N uptake was not significant.

4.5.2 Effect of fertigation regimes and rice based cropping systems on phosphorus content and uptake by rice

The data regarding the effect of fertigation regimes and rice based cropping systems on phosphorus content (%) and uptake (kg ha^{-1}) by rice grains and straw and is presented in table 4.12. P content and uptake in rice straw was found to be significantly lower in W_2 in comparison to W_1 and W_3. The content and uptake of P in rice straw was found to be significantly higher in rice-durum wheat cropping system in comparison to other cropping systems. A significant interaction of fertigation regimes and cropping systems was found in terms of the P content and uptake by straw under various treatment combinations.

Table 4.11 Effect of fertigation regimes and rice based cropping systems on nitrogen content (%) and uptake (kg ha^{-1}) by rice.

Treatments	N content in straw				N content in grain				N uptake by straw				N uptake by grain				Total N uptake			
	W1	W2	W3	Mean	W1	W2	W3	Mean	W1	W2	W3	Mean	W1	W2	W3	Mean	W1	W2	W3	Mean
C1	0.76	0.78	0.86	**0.80**	1.35	1.34	1.29	**1.33**	27.13	38.61	44.17	**36.64**	41.90	48.65	55.18	**48.58**	69.03	87.26	99.35	**85.21**
C2	0.64	0.81	0.93	**0.80**	1.31	1.14	1.31	**1.25**	26.28	38.21	45.93	**36.80**	39.61	38.66	44.55	**40.94**	65.89	76.87	90.48	**77.75**
C3	0.80	0.72	0.79	**0.77**	1.24	1.32	1.37	**1.31**	31.24	33.84	43.41	**36.17**	35.63	43.45	46.52	**41.86**	66.87	77.29	89.93	**78.03**
C4	0.83	0.67	0.81	**0.77**	1.37	1.35	1.10	**1.28**	31.49	32.48	38.57	**34.18**	36.67	45.83	38.58	**40.36**	68.16	78.32	77.15	**74.54**
Mean	**0.76**	**0.74**	**0.85**		**1.32**	**1.29**	**1.27**		**29.04**	**35.79**	**43.02**		**38.45**	**44.15**	**46.21**		**67.49**	**79.93**	**89.23**	
LSD(0.05)W:C::WxC	NS:NS::NS				NS:NS::0.14				NS:NS::NS				5.57:6.32::NS				NS:NS::NS			

C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crops

Table 4.12 Effect of fertigation regimes and rice based cropping systems on phosphorus content (%) and uptake (kg ha^{-1}) by rice.

Treatments	P content in straw				P content in grain				P uptake by straw				P uptake by grain				Total P uptake			
	W1	W2	W3	Mean	W1	W2	W3	Mean	W1	W2	W3	Mean	W1	W2	W3	Mean	W1	W2	W3	Mean
C1	0.18	0.06	0.18	**0.14**	0.37	0.44	0.38	**0.40**	6.53	2.89	9.51	**6.31**	11.34	16.04	15.73	**14.37**	17.87	18.93	25.24	**20.68**
C2	0.09	0.07	0.11	**0.09**	0.37	0.35	0.35	**0.36**	3.56	3.21	5.20	**3.99**	11.25	11.82	11.67	**11.58**	14.81	15.03	16.87	**15.57**
C3	0.17	0.08	0.09	**0.11**	0.36	0.36	0.40	**0.38**	6.61	3.99	4.67	**5.09**	10.22	11.85	13.59	**11.89**	16.83	15.85	18.26	**16.98**
C4	0.12	0.09	0.10	**0.10**	0.55	0.41	0.39	**0.45**	4.35	4.14	4.71	**4.40**	13.47	13.97	13.73	**13.72**	17.82	18.10	18.44	**18.12**
Mean	**0.14**	**0.07**	**0.12**		**0.41**	**0.39**	**0.38**		**5.26**	**3.56**	**6.02**		**11.57**	**13.42**	**13.68**		**16.83**	**16.98**	**19.70**	
LSD(0.05)W:C::WxC	0.01:0.01::0.01				NS:0.07::NS				1.75:1.03::1.79				NS:1.21::2.09				NS:1.54::2.26			

C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crops

P content and uptake in rice grains was found to be statistically similar across various fertigation regimes. The content of P in rice grains was found to be significantly higher in rice-lentil cropping system in comparison to rice-barley and rice-chickpea cropping systems. The uptake of P in rice grains was found to be significantly higher in rice-lentil and rice wheat cropping systems in comparison to rice-chickpea and rice-barley cropping systems. In terms of total P uptake by the rice crop, no significant effect of various fertigation regimes was observed. Total P uptake by rice crop was significantly higher in rice-lentil and rice-wheat cropping systems in comparison to rice-chickpea and rice-barley cropping systems. Total P uptake by rice crop was significantly higher in rice-wheat cropping system in comparison to rice-lentil cropping system. The interaction of fertigation regimes and cropping systems produced significant differences in P content in rice straw and P uptake by rice grains among various treatment combinations. A significant interaction of fertigation regimes and cropping systems was also found in terms of the total P uptake by rice crop under various treatment combinations.

4.5.2 Effect of fertigation regimes and rice based cropping systems on potassium content and uptake by rice.

Table 4.13 presents the data regarding K content and uptake in rice grains and straw and total uptake of K by the rice crop under different treatments. K content in rice straw was found to be significantly more in rice durum wheat cropping system than the other three cropping systems. The effect of various fertigation regimes and cropping system was found to be non-significant in terms of K content in rice grains and K uptake by rice straw and grains. The effect of various fertigation regimes and cropping systems on total K uptake by the rice crop was found to be non-significant. A significant interaction of fertigation regimes and cropping systems was also found in terms of the K content in rice grains under various treatment combinations. Besides, the interaction

Table 4.13 Effect of fertigation regimes and rice based cropping systems on potassium content (%) and uptake (kg ha^{-1}) by rice.

Treatments	K content in straw				K content in grain				K uptake by straw				K uptake by grain				Total K uptake			
	W1	W2	W3	Mean	W1	W2	W3	Mean	W1	W2	W3	Mean	W1	W2	W3	Mean	W1	W2	W3	Mean
C1	1.92	2.08	2.30	**2.10**	0.32	0.31	0.27	**0.30**	69.43	103.12	118.44	**97.00**	9.81	11.28	11.65	**10.92**	79.25	114.41	130.09	**107.91**
C2	1.74	1.89	1.99	**1.87**	0.31	0.31	0.23	**0.28**	71.14	89.18	98.18	**86.17**	9.41	10.53	7.89	**9.28**	80.55	99.71	106.07	**95.45**
C3	1.83	2.08	1.93	**1.95**	0.31	0.29	0.31	**0.30**	67.06	98.92	105.58	**90.52**	8.78	9.71	10.45	**9.65**	75.84	108.63	116.03	**100.17**
C4	1.83	1.86	1.87	**1.85**	0.31	0.29	0.33	**0.31**	68.22	87.27	88.87	**81.45**	8.27	9.83	11.56	**9.89**	76.48	97.10	100.42	**91.34**
Mean	**1.83**	**1.98**	**2.02**		**0.31**	**0.30**	**0.28**		**68.96**	**94.62**	**102.77**		**9.07**	**10.34**	**10.39**		**78.03**	**104.96**	**113.15**	
LSD(0.05)W:C::WxC	NS:0.15::NS				NS:NS::0.15				NS:NS::NS				NS:NS::NS				NS:NS::NS			

C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crop

effect of fertigation regimes and cropping systems was found to be non-significant in terms of K content in rice straw and K uptake by rice straw and grains and total uptake of K.

4.6 Effect of fertigation regimes and rice based cropping systems on various nutrient use efficiency indices

4.6.1 Effect of fertigation regimes and rice based cropping systems on internal nutrient use efficiency of N, P and K

The data regarding the effect of rice based cropping systems and fertigation regimes on internal nutrient use efficiency of rice crop in terms of N, P and K is presented in table 4.14. No significant effect of various fertigation regimes was observed on internal N, P and K use efficiency of rice plants. A significant effect of cropping systems on the internal nutrient use efficiency of P was observed. Rice-barley cropping system has significantly greater internal phosphorus use efficiency than the other three cropping systems. No significant effect of cropping system was found on the internal use efficiency of nitrogen and potassium.

4.6.2 Effect of fertigation regimes and rice based cropping systems on partial factor productivity of applied nutrients

The data in table 4.15 shows that the partial factor productivity of applied nutrients was significantly affected by fertigation regimes in case of N, P and K. The partial factor productivity of applied nitrogen was significantly greater under W_1 fertigation regime than the other two. In case of phosphorus and potassium, it was significantly greater under W_2 and W_3 fertigation regimes in comparison to W_1.

4.6.3 Effect of fertigation regimes and rice based cropping systems on nutrient harvest indices

Table 4.14 Effect of fertigation regimes and rice based cropping systems on Internal Nutrient use efficiency (kg kg^{-1})

	N				P				K			
Treatment	W1	W2	W3	Mean	W1	W2	W3	Mean	W1	W2	W3	Mean
C1	45.21	41.92	42.95	**43.36**	175.54	192.79	170.70	**179.68**	41.00	31.96	33.15	**35.37**
C2	46.34	46.72	37.90	**42.78**	204.90	225.55	202.12	**210.86**	38.58	34.27	33.50	**35.45**
C3	43.77	42.81	37.73	**41.44**	172.00	208.76	185.84	**188.87**	39.79	30.59	29.89	**33.42**
C4	39.62	44.86	45.82	**43.43**	149.34	188.73	190.81	**176.27**	35.38	35.05	35.33	**35.25**
Mean	**43.73**	**43.42**	**41.10**		**175.45**	**203.96**	**187.36**		**38.69**	**32.97**	**32.97**	
LSD(0.05)W:C::WxC	NS:NS::NS				NS:20.49::NS				NS:NS::NS			

C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crops

Table 4.15 Effect of fertigation regimes and rice based cropping systems on Partial factor productivity of applied nutrients (kg kg^{-1})

Treatment	N				P				K			
	W1	W2	W3	Mean	W1	W2	W3	Mean	W1	W2	W3	Mean
C1	155.3	91.4	71.4	**106.0**	77.7	91.4	107.1	**92.1**	155.3	182.8	214.3	**184.1**
C2	152.1	84.5	56.8	**97.8**	76.0	84.5	85.2	**81.9**	152.1	169.1	170.5	**163.9**
C3	144.2	83.1	56.4	**94.6**	72.1	83.1	84.7	**80.0**	144.2	166.3	169.3	**159.9**
C4	135.3	85.0	58.6	**93.0**	67.7	85.0	87.9	**80.2**	135.3	169.9	175.7	**160.3**
Mean	**146.7**	**86.0**	**60.8**		**73.4**	**86.0**	**91.2**		**146.7**	**172.0**	**182.4**	
LSD(0.05)W:C::WxC	28.76:NS::NS				11.76:NS::NS				23.51:NS::NS			

C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crops

Table 4.16 shows the effect of cropping systems and fertigation regimes on nutrient harvest index in terms of N, P and K. No significant effect of fertigation regime or cropping system was reflected on nitrogen and potassium harvest indices. The phosphorus harvest index was significantly affected by fertigation regimes as well as cropping systems. Phosphorus harvest index was significantly greater for W_2 in comparison to W_1 and W_3. Phosphorus harvest index was significantly lower for rice-durum wheat cropping system in comparison to the other three cropping systems. The phosphorus harvest index was significantly greater for rice-lentil system in comparison to the other three cropping systems. The phosphorus harvest index was significantly greater for rice-lentil system in comparison to the rice chick pea and rice-durum wheat cropping systems. A significant interaction of fertigation regimes and cropping systems was also found in terms of the phosphorus harvest index of rice under various treatment combinations.

4.6.4 Effect of fertigation regimes and rice based cropping systems on Physiological Nutrient Use Efficiencies of N, P and K

Table 4.17 shows that there was no significance effect of fertigation regimes and cropping systems on the physiological nitrogen use efficiency in the rice crop. The physiological phosphorus use efficiency of rice was significantly higher under W_2 and W_3 fertigation regimes than W_1 fertigation regime. The physiological phosphorus use efficiency of rice was significantly higher under rice-barley and rice-chickpea cropping systems in comparison to rice-durum wheat and rice-lentil cropping systems. The physiological potassium use efficiency of rice was significantly higher under W_1 fertigation regime and lower under W_2 and W_3 fertigation regimes. The effect of cropping systems on physiological use efficiency of potassium in rice was found to be non-significant. No significant interaction of fertigation regimes and cropping systems was found in terms of the physiological N and K use efficiency of rice under various treatment combinations.

Table 4.16 Effect of fertigation regimes and rice based cropping systems on nutrient harvest indices (%) of N, P and K.

Treatments	N				P				K			
	W1	W2	W3	Mean	W1	W2	W3	Mean	W1	W2	W3	Mean
C1	61.17	50.40	55.36	**57.47**	63.628	84.62	62.32	**70.18**	12.57	9.88	9.04	**10.49**
C2	59.80	56.16	49.53	**53.24**	76.063	78.63	69.16	**74.62**	11.85	10.67	7.91	**10.14**
C3	54.36	61.07	51.66	**54.06**	62.18	75.38	74.52	**70.69**	12.19	8.93	9.02	**10.10**
C4	55.88	55.36	50.34	**55.21**	75.91	77.20	74.70	**75.93**	10.77	9.24	11.60	**10.83**
Mean	**57.39**	**55.88**	**51.72**		**69.44**	**78.96**	**70.17**		**11.85**	**9.89**	**9.44**	
LSD(0.05)W:C::WxC	NS:NS::NS				5.46:4.53::7.85				NS:NS::NS			

C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crop

Table 4.17 Effect of fertigation regimes and rice based cropping systems on physiological use efficiency (kg kg^{-1}) of N, P and K.

	N				P				K			
Treatments	W1	W2	W3	Mean	W1	W2	W3	Mean	W1	W2	W3	Mean
C1	97.8	99.2	95.0	**97.4**	374.8	456.9	374.9	**402.2**	86.8	75.3	72.7	**78.3**
C2	108.6	105.3	92.0	**102.0**	480.6	539.0	494.6	**504.8**	89.6	81.6	79.9	**83.7**
C3	99.6	103.9	97.7	**100.4**	390.6	507.3	481.6	**459.7**	88.5	74.4	76.9	**79.9**
C4	94.7	107.1	107.3	**103.0**	357.8	450.2	447.6	**418.5**	84.7	83.7	82.7	**83.7**
Mean	**100.2**	**103.9**	**98.0**		**401.0**	**488.4**	**449.6**		**87.4**	**78.7**	**78.0**	
LSD(0.05)W:C::WxC	NS:NS::NS				56.4:40.5::NS				7.6:NS::NS			

C_1=Rice-Durum Wheat, C_2=Rice-Barley, C_3=Rice-Chickpea, C_4=Rice-Lentil
W_1= N @ 20 kg ha^{-1} in rice through fertigation followed by 200 mm irrigation through inline drip system in post-rice crops
W_2= N @ 40 kg ha^{-1} in rice through fertigation followed by 300 mm irrigation through inline drip system in post-rice crops
W_3= N @ 60 kg ha^{-1} in rice through fertigation followed by 400 mm irrigation through inline drip system in post-rice crops

Discussion

DISCUSSION

This investigation has been conducted based on the premise that the rainfed rice based cropping systems need to be improved upon in terms of their diversity and intensity for any increase in the system productivity, which is inherently low for the rainfed rice based systems of south Bihar. There is not only ample scope for increasing the rainfed rice productivity but also sufficient scope for increasing the system productivity by targeting the *rabi* season when the fields usually remain fallow or are cultivated with abysmally low yields.

There have been efforts for sustainable intensification and diversification of rainfed rice based systems for increasing system productivity but with little success on the ground. As water is the prime limiting factor in deciding the productivity of these systems, supplemental life-saving irrigation, if made available through rainwater harvesting or any other means can be a game changer. When water is limiting, it merits application through efficient delivery mechanisms such as drip and sprinklers. And once these systems are in place, they can also be used for efficient nutrient delivery. This can increase the choice of crops to be grown and increase the attainable yields. This investigation has thus been planned based on the hypothesis that the fertigation in various rice based systems, is likely to influence the crop growth and yields with associates changes in the soil physical conditions as well as nutrient relations. The salient results of this investigation are being discussed under prominent sub-heads in this chapter.

5.1 Rice growth and yield parameters as influenced by various fertigation regimes and cropping systems

At the early stages growth, a direct seeded rice plant may utilize soil nitrate nitrogen plus ammonium nitrogen accumulated during the previous crop before it is lost through leaching and / or denitrification. During the active tillering and panicle initiation stages of rice crop growth, in

W_3 fertigation regime, more nitrogenous fertilizer is applied and as this application is at the effective root zone depth, so there is less scope of loss of nitrogen, and vegetative growth as well as root growth of plant is maximum. The grain yield was greater in W_3 and W_2 fertigation regimes with no significant difference in no of panicles m^{-2}, no of tillers m^{-2} and canopy height. Fertigation levels, can often influence various yield contributing characters leading to differences in grain yield (Sharma *et al.*, 1995). Patil *et al*. (2001) observed that in direct seeded rice based cropping systems (rice-chickpea and rice-fallow) in rainfed lowlands, rice grain yield increased significantly in response to applied N up to 120 kg/ha during 1996 and 1998; and there was also a significant effect of cropping systems. Soman (2012) also found that rice yield under fertigation was 3.8 t/ha in comparison to a yield of 3.1 t/ha under flood irrigation. He reported that keeping the soil wet alone and not providing standing water resulted in yields comparable to or more than that in flooded (with standing water) condition. Sun *et al*. (2012) demonstrated that the optimum N application strategy was beneficial to simultaneously improve grain yield and WUE, indicating that water and N-fertilizers are the two most important factors with interaction effects on rice yield and WUE.

5.2 In situ measurements in the soil system

5.2.1 The effect of different fertigation regimes and rice based cropping systems on soil profile penetration resistance

Penetration resistance values are used to characterize soil compaction, which influences the structural characteristics and functions of soils (Hakansson and Lipiec, 2000; Abu-Hamdeh, 2002). Soil profile penetration resistance measured in the experimental plots during May 2016 after the harvest of *rabi* season crops but before rice crop establishment was usually higher than that measured after the harvesting of rice crop. During the month of May, after the *rabi* season

crops are harvested, the profile soil moisture availability is low, soil is hard and resists the penetrometer penetration. Therefore, high penetration resistance was encountered and on an average, penetration resistance at the surface of the soil started from about 1700 kpa across three fertigation regimes. Here soil penetration resistance was found to increase with soil depth up to about 15 to 20 cm depth. The differences in the soil profile penetration resistance across different fertigation regimes and cropping systems before rice crop establishment in May 2016 (Figures 4.1 and 4.2) may be explained on the basis of differential organic matter inputs across these treatments. Lower penetration resistance in organic manure treated plots has been reported (Xin *et al*., 2016). The *rabi* season crops in this experiment namely durum wheat, barley, lentil and chickpea have widely varying shoot biomass as well as root biomass production levels. Differential root biomass in the profile produced by these crops would have added differential levels of organic matter into the profile, which definitely has been reflected in the soil profile penetration resistance. These effects were found to be short lived as subsequent observations of soil profile penetration resistance after harvesting of rice crop found no observable difference in terms of the influence of various fertigation regimes and cropping systems. The effect of various fertigation regimes on the profile penetration resistance after the *rabi* season harvest is nullified by the time of harvest of the subsequent rice crop in the system, probably because the differential organic matter addition in various plots would likely get decomposed by the end of the rice season. Moreover, the organic matter inputs during the rice crop were almost similar across all treatments, as reflected in the statistically similar straw yields across all fertigation regimes and cropping systems.

The three rice fertigation regimes reflect a distinct trend of variation in soil profile penetration resistance with depth. Treatments with higher levels of irrigation water application

through fertigation, show a trend of a steeper increase in profile penetration resistance up to about 25-30 cm depth followed by a similarly steeper decrease in penetration resistance. This could likely be explained due to greater disruption of soil aggregates on account of rapid movement of water in dry soils resulting from fertigation. Thus breakage of aggregates due to the effect of entrapped air escaping from the aggregates would have ultimately resulted in soils with greater penetration resistance. The four rice based cropping systems demonstrate distinct trends of variation in penetration resistance with depth in the profile. In rice lentil cropping system, the penetration resistance appears to be higher at all depths in comparison to other cropping systems (Figure 4.3). This could probably be due its low root biomass and root penetration in comparison to other cropping systems. So its penetration resistance is high and the slope of the trend line between penetration resistance and soil depth is high, reflecting a sharp increase in penetration resistance down the profile. Before rice crop establishment, in rice-chickpea cropping system, the PR was usually lower than rice-lentil cropping system (Figure 4.3) but higher than rice-durum wheat and rice-barley cropping systems. This can also be attributed to lower root biomass and root penetration of chickpea in comparison to the cereal crops. Overall, it appears that long term effects of fertigation and cropping systems on soil profile penetration resistance might be prominent and long lasting, but as the system at present is under differential fertigation and cropping systems for last two years only, the effects seem to reflect a seasonal cycle.

5.2.2 Effect of fertigation regimes and rice based cropping systems on steady state infiltration rate of soil

The un-replicated observations of steady state infiltration rate, presented in table 4.3 indicate that the infiltration rate was found to be lower in rice-legume cropping systems (both chickpea and lentil) in comparison to all cereal based cropping systems. It may be due to lower

rooting depth in case of leguminous crops than cereal based cropping system. Here the cumulative infiltration rate was plotted against cumulative lapse time under various fertigation regimes and cropping systems measured after the harvest of the third rice crop in the system during November, 2016 have been shown in figures 4.5, 4.6 and 4.7. These curves show that there are heterogeneities in the system, which can better be characterized and described with greater confidence by replicated observations. Higher infiltration in ZT plots compared to CT (dry or wet) plots might be due to the minimal disturbance that maintained the continuity of water conducting pores and the improvement in soil aggregation (Dwivedi *et al*., 2012). According to, Singh *et al*. (2016) the increase in infiltration rate in zero tilled cereal based cropping system was possibly due to improvement in aggregate stability (see Table 4.3). Many researchers (Bhattacharyya *et al*., 2008; Li *et al*., 2007b) have reported higher infiltration rate (initial as well as steady state) under zero tillage and residue retention compared to conventional tillage and removal of residues. Shaver *et al*. (2002) found that infiltration characteristics of the soil depend on the aggregation, and size distribution, geometry, continuity, and stability of the pores.

5.3 Effect of fertigation regimes and rice based cropping systems on soil physical properties

5.3.1 Effect of fertigation regimes and rice based cropping systems on soil bulk density

No significant effect of various fertigation regimes and the studied cropping systems on bulk density of the surface soil was found in measurements made using soil cores after harvest of the rice crop during November, 2016. Although significant effects of various rice based cropping systems were observed during the analysis of soil samples drawn before rice crop establishment, these have not translated into any significant differences in bulk density across various cropping systems. Profuse plant root development in soils tends to produce soils with a higher bulk density

(Brady and Weil, 2002). However, in the present study, the differences in root profuseness expected under various cropping systems are not reflected in the bulk density measurements that have been taken only after the harvest of the rice crop. It is likely that the differences might be prominent after the harvest of the *rabi* season crops. Meena *et al*. (2015) reported from a short-term (3 years) study that some changes in soil properties may not actually stay over a long-period, but could be indicator of the direction of changes. The lack of significant effects on such soil properties may also be due to high field variability and short duration under these cropping systems and fertigation regimes. Mukherejee and Lal (2015) also reported that the lack of significant effects of cover crops on some soil properties could be due to high field variability and short duration under cover cropping.

5.3.2 Effect of fertigation regimes and rice based cropping systems on maximum water holding capacity of soil

The maximum water holding capacity of surface soil after the harvest of *rabi* season crops was found to be significantly greater under W_2 (44.12%) and W_3 (44.89%) fertigation regimes in comparison to that under W_1 (42.12 %) fertigation regime, probably because of the effects of irrigation regimes on wetting and drying cycles of the soil. Frequent irrigation resulting from fertigation increases the frequency of wetting and drying cycles in soil. Amount of irrigation water applied at each instance affects the amplitude of these wetting drying cycles. The soil conditions under these differing wetting drying cycles can create differential root growth patterns, differential root exudation, plant growth and litter fall, which in turn can potentially affect the inputs of organic matter into the soil. It is quite possible that the differential organic matter inputs do not result in any long term differences in soil organic matter content across various treatments due to harsh climatic conditions after the harvest of *rabi* season crops. Meena

et al. (2015) also reported from a short-term (3 years) study that some changes in soil properties may not actually stay over a long-period, but could be indicator of the direction of changes.

However, it appears, that the structural improvements resulting from organic matter inputs can last comparatively longer because of little influence of anthropogenic activities in the absence of tillage. Thus the probable increase in soil pore space in W_2 and W_3 fertigation regimes might have resulted in an increase in the maximum water holding capacity of surface soil. The maximum water holding capacity in various treatments at lower depths are found to be statistically similar probably because the effects of wetting drying cycles in fertigation are generally restricted to the upper layers of the soil. Moreover, the differential organic matter inputs from leaf litter and root exudation are also expected to be more prominent in the upper layers of the soil profile. Decrements in organic materials at lower soil depth have been reported to decrease water holding capacity of soils (Bandyopadhyay *et al*., 2011; Barzegar *et al*., 2002). Thus, the soil physical conditions resulting from fertigation treatments in the post rice crops are more likely to have short term effects visible in ephemeral soil physical properties such as maximum water holding capacity in the upper layers of the soil profile. However, the fertigation treatments in the *kharif* season involving differential nitrogen inputs have had no significant effect visible on maximum water holding capacity, probably because even a rainfed rice crop during the times of a good monsoon under lowland conditions often encounters prominent wetting and drying cycles, which under high temperature conditions, might lead to high rates of organic matter decomposition and then the subsequent wetting drying events also break the aggregates. Thus no significant differences in maximum water holding capacity of the soils were observed across various fertigation regimes after the harvest of the rice crop. The mean value of

maximum water holding capacity of soils after the rice crop harvest was found to decrease with depth ($MWHC_{0\text{-}15cm}$ = 46.75 > $MWHC_{15\text{-}30cm}$ = 45.57 > $MWHC_{30\text{-}45cm}$ = 44.61).

5.3.3 Effect of various fertigation regimes and rice based cropping systems on wet aggregate stability of surface soil

The mean weight diameter (MWD) and geometric mean diameter (GMD) of water stable aggregates of surface soils from the experimental plots varied from 0.18 mm to 0.36 mm and 0.36 mm to 0.41 mm, in the same order. After the harvest of the third rice crop in the system, the MWD and GMD were found to be in the range of 0.68 to 1.58 mm and 0.42 to 0.55 mm respectively (Table 4.6). Direct seeded rice (DSR) that avoids inversion of soils and disruption of soil structure by tillage protects organic matter from decomposition, and thus leads to an increment in MWD and GMD and water stable micro-aggregates (Choudhury *et al*., 2014; Cambardella and Elliott, 1992). No significant effect of treatments *viz*., fertigation levels and cropping systems were found in terms of the wet aggregate stability of surface soil aggregate samples collected during May 2016. However, among the surface soil aggregate samples collected during November 2016, the aggregates collected from plots representing the W_3 and W_2 fertigation regimes (corresponding to N fertigation @60 and 40 $kgha^{-1}$) exhibited significantly greater MWD of water stable aggregates (1.22 mm and 1.20 mm) in comparison to W_1 fertigation level (corresponding to N fertigation @ 20 kg ha^{-1}) where with MWD of water stable aggregates was 0.77 mm. The Geometrical Mean Diameter (GMD) of water stable aggregates calculated from the size distribution (by weight) of water stable aggregates was also found to be significantly higher for both W_2 and W_3 (0.49mm in both the cases) fertigation regimes in comparison to a value of 0.44 mm in W_1 fertigation regime from among the soil samples drawn after the harvest of rice crop. In *rabi* season, 400 mm irrigation water application

in W_3 fertigation regime might have led to more favourable conditions for decomposition of soil organic matter as compared to compared to W_1 where only 200 mm irrigation was provided through fertigation. During the rice crop season, W_3 fertigation treatment involved a higher level of N application @60 kg ha^{-1}, which might have led to more vegetation, root growth and rhizo-deposition (Bandyopadhyay *et al*., 2011) in the system resulting in an associated increase in MWD and GMD of water stable aggregates from soil surface aggregate samples collected after harvesting of rice crop. Introduction of legume based cropping system *viz*., Chickpea and Lentil could also have had significant nitrogen addition from biological fixation and are expected to increase both the MWD and GMD of water stable aggregates in comparison to those of samples drawn from all cereal based cropping systems namely rice-durum wheat and rice-barley system during November, 2016. However, probably because of far greater application of nitrogen through chemical fertilizers in the cereal-rice cropping systems in comparison to rice-legume systems (120 and 80 kg N fertilizer application per ha in C_1 and C_2, in comparison to 18 kg N fertilizer application each in C_3 and C_4), no significant differences in the size of water stable aggregates was observed across various rice based cropping systems. Bhattacharyya *et al*. (2009) found that management practices *viz*., zero tillage and legume-based cropping sequences have the potential to improve soil aggregation. They claimed that crop rotations had no significant effect on aggregate stability of different size fractions of surface soil layers after completion of three year rotation. Inclusion of legumes crops compared to cereals in rotations might result in enhancing microbial activity, fixing atmospheric nitrogen and higher soil organic carbon but simultaneously leads to faster and easier decomposition creates stable aggregates (Gangwar *et al*., 2006; Bandyopadhyay *et al*., 2016). Mahboubi and Lal (1998) reported that favourable effects of ZT on soil structural properties may be partly also due to higher earthworm activity

and addition of more microbial biomass in soil. Similar to the results of this study, several authors (Bissonnette *et al*., 2001; Whalen *et al*., 2003) reported that improvements in aggregation can occur within 2–3 years of establishing conservation practices. Other study suggested that N fertilizers that contain or form ammonium ions may tend to reduced aggregate stability by dispersing organic binding agents inside aggregates and soil colloids (Fonte *et al*., 2009).

5.4 Effect of fertigation regimes and rice based cropping systems on soil chemical properties

5.4.1. Effect of fertigation regimes and rice based cropping systems on wet oxidizable carbon content of soils

Various fertigation regimes were found to be significantly affecting the soil organic carbon content at the depths of 0-15, 15-30 and 30-45 cm depths in samples collected before rice crop establishment during May 2016 (Table 4.7). The cereals crops have a deeper root system than legume crops and in the present situation, the roots remained undisturbed in the root zone due to absence of tillage zero tillage, which might facilitate slower decomposition of organic carbon resulting in its short term accumulation in deeper root zones i.e., in 15-30 cm soil layer through. This effect was not so prominent in the still deeper soil layer (30-45 cm) due to absence of sufficient root biomass in that zone and other factors might have come into play. At the depth of 30-45 cm, significantly higher soil organic carbon was found in the rice lentil cropping system in samples drawn before rice crop establishment during May, 2016. This could be due to more biological fixation of nitrogen and low water use in lentil, which allowed more decomposition of organic matter and its movement down the profile with water applied through fertigation. Further, more nitrogen availability along with more water available through fertigation could

have allowed more nitrogen to leach to the deeper zone and then have led to the decomposition of the previous season's (rice crop) roots and increased the oxidisable organic carbon content. Mishra *et al.* (2015) reported that after 3rd year direct seeded rice with brown manuring followed by zero tilled wheat, there was a significantly higher gain in total soil organic carbon in the 0-30 cm soil layer. The application of balanced mineral fertilizers (NPK) significantly increased SOC content by increasing the accumulation of root biomass in soil over time (Zhao *et al*., 2013). There could be another possible reason for increasing soil organic carbon in cereal based cropping systems, i.e. higher amount of rice straw K content in rice durum wheat cropping system. Besides this in rice-cereal systems, there is higher amount of application of K fertilizers in both *rabi* and *kharif* seasons. Organic carbon in soils varied significantly as influenced by the use of K fertilization either from inorganic (MOP) or from organic (rice straw) sources (Saha *et al*., 2009). Organic carbon ranged from 1.05 per cent (straw removed) to 1.43% (straw retained). The use of K fertilizer either alone or in combination with rice straw significantly increased the organic carbon level (Saha *et al*., 2009).

5.4.2. Effect of fertigation regimes and rice based cropping systems on available nitrogen of soil at various depths

The data in table 4.8 shows that the effect of various fertigation regimes on available nitrogen in the soil surface layer was non-significant after the harvest of *rabi* season crops in May 2016 as well as after the harvest of the rice crop in November, 2016. At greater depths, i.e., at 15-30cm and 30-45 cm soil depths, more nitrogen was available in treatments receiving less irrigation through fertigation during the *rabi* season. This could be because of greater uptake of nitrogen from deeper soil layers in treatments receiving larger inputs of water through fertigation. However, this trend did not persist after the harvest of the rice crop. The data shows

that before the rice crop establishment, there was no significant difference in the available nitrogen content across various cropping systems at any of the depths. However, after the harvest of the rice crop, the available nitrogen content in the soil surface was minimum in rice-chickpea cropping system followed by that in the rice durum wheat cropping system and maximum in rice-barley and rice-lentil cropping system, both of which were statistically similar. This may be attributed to relatively greater mineral fertilizer N addition in cereals. For instance the mineral fertilizer addition in durum wheat, barley, lentil and chickpea amounted to 120, 80, 18 and 18 kg ha^{-1}, respectively. Such huge differences in external fertilizer N inputs can mark the effect of biological nitrogen fixation. The available nitrogen content in the 15-30 cm and 30-45 cm soil layers was also significantly lower in rice-chickpea cropping system in comparison to other cropping systems. This is also attributable to the large differences in the external N inputs in these cropping systems, which possibly leached to the lower layers of the profile to increase their nitrogen content. Before rice crop establishment, cropping systems and fertigation regimes were found to interact significantly to create statistically significant differences in available nitrogen in 15-30 cm soil layer among various treatment combinations. After the harvest of rice crop, the interactions of fertigation regimes and cropping systems created statistically significant differences in available nitrogen content among various treatment combinations in the soil surface layer as well as in the 30-45 cm soil layer. In general, the available nitrogen content was lowest in rice chickpea cropping system and that too at higher levels of fertigation. The available soil N varied from 130.2 to 165.9 kg ha^{-1} with a mean of 146.3 kg ha^{-1} before rice crop establishment and varied from 119.7 to 155.4 kg ha^{-1} with a mean of 137.6 kg ha^{-1} after harvesting of rice for surface soil (Table 4.8). There was no significant effect of various fertigation regimes on availability of soil nitrogen in the surface soil both before rice crop

establishment as well as after the harvest of the rice crop. This suggests similar depletion of soil N after rice crop even with the application of N at varied levels through fertigation or even varying N additions to the system resulting from litter fall, root exudation or biological nitrogen fixation under various cropping systems. Similar depletion of soil N was also found in 15-30 cm soil from 138.3 to 133.0 kg ha^{-1} and subsurface (30-45 cm) 133.2 to 130.2 kg ha^{-1} before and after cultivation of rice respectively. Overall, available N content was found to be decreasing with soil depth. Soil N availability along depth might be reduced due to a decline in organic C content, lower plant root density and lower biological activity (Batjes, 1996; Benbi and Senapati, 2010). Among the cropping systems, soil with rice-barley system showed greater amount of soil N (151.9 kg ha^{-1}) followed by both rice-chick pea and rice-lentil (146.3 kg ha^{-1}) system and then rice-durum wheat system (140.7 kg ha^{-1}) before rice crop establishment in the surface soil. This seems absurd keeping in view that chickpea and lentil are grain legumes which are known to fix substantial amounts of atmospheric nitrogen to the soil. However, due consideration must be given to the basal doses of applied N for barley along with its well-developed root penetration up to 150 cm soil depth (Singh, 1996). Barley may uptake less N from surface soil layer compared to Wheat. N responses have been reported for annual cropping systems, in which a cereal is followed by a legume or a double crop systems where the cereal is sown after harvest of the legume (Shah *et al*., 2003). An increment in available N content is found in rice-chickpea and rice-lentil (146.3 kg ha^{-1}) system compared to rice durum wheat (140.7 kg ha^{-1}) due to fixing of atmospheric N by legumes which allows cropping in N-impoverished soils without external fertilizer N inputs. The nodulated roots and above ground residues, remaining after the seed and other components of the crop have been harvested, represent a potentially valuable source of N for replenishing soil N pools (Giller, 2001).

Improved management of nitrogen in low nitrogen soils is the criteria for increasing soil productivity and economic sustainability. Water-saving irrigation and high nitrogen use efficiency are becoming more important in rice production aimed at high and stable yield due to the shortage of water resources and the spread of non-point source pollution caused by irrational fertilization (Sun *et al*., 2012). The available soil N is found to have declined from 146.3 to 137.6 kg ha^{-1}, 138.3 to 133.0 kg ha^{-1} and 133.2 to 130.2kg ha^{-1} in 0-15, 15-30 and 30-45 cm soil depth when samples drawn before rice crop establishment are compared with those drawn after harvesting of rice irrespective of cropping systems and fertigation levels (60, 40 and 20kg/ha) (Table 4.8). Environmental losses of N due to denitrification and leaching coupled with crop uptake by rice decreased the available N content in soil (Mohanty *et al*., 2012). However, among different fertigation levels, soil nitrogen varied significantly in samples drawn from 15-30 cm and 30-45 cm depth during May, 2016. Due to greater external application of nitrogen for cereal crops in *rabi* season, there was an increased soil nitrogen availability at 15-30 cm soil layer. Significant effects of fertigation on available N status of soil in deeper soil layers suggest that N management and water management may go hand in hand. Planning the use of both these resources should consider the profile movements of each in complement to each other. Soil aeration improvement promotes more nutrient supply from soil or more oxygen supply to the root system, would produce and supply more assimilates to the functional leaf, further improve the assimilation of inorganic N (Sun *et al*., 2012). However, excessive N application in rice crop supports for more uptake of N by rice and declined N content in soil after rice harvesting.

5.4.3. Effect of fertigation regimes and rice based cropping systems on soil available phosphorus

Table 4.9 demonstrates that both before rice crop establishment as well as after the harvest of the rice crop, no significant effect of any fertigation regime was observed in terms of P availability in the surface as well as the sub-surface soil layer. This is expected as the fertigation levels did not vary in terms of P fertilizers. At the depth of 30-45 cm, soil available P was significantly greater in W_3 in comparison to W_2 and W_1 and also in W_2 in comparison to W_1 before the rice crop establishment. This scenario has resulted due to differential uptake of P under differential fertigation regimes (which varied in terms of the amount of irrigation water applied during the *rabi* season). After the harvest of rice crop, soil available P was still significantly greater in W_3 in comparison to W_2 and W_1, but W_2 and W_1 were statistically at par with each other. Rice during rainy season (June–September) is often fed with rainfall and remains wet. However, dry spell may occur intermittently. After rice harvest in the post-rainy season (November–May) due to lack of sufficient rainfall or irrigation facilities crops may suffers from dry spell (Kar and Kumar, 2009). These wet and dry cycles have great impact on plant nutrition (Kirk *et al*., 1998; Kato *et al*., 2016). Irrigation through fertigation and available soil moisture cause more P sufficiency in soil (Seng *et al*., 1999; Bandyopadhyay *et al*., 2016). The possible explanation for this phenomenon is that even after substantial application of fertilizer P in rice, there is possibly more uptake of P from treatments with lower levels of fertigation, albeit the lower fertigation in the rice season is in terms of lower N fertilizer inputs. Before rice crop establishment, the average P availability was significantly higher in rice lentil cropping system than in rice chickpea cropping system, both of which had significantly higher P availability than rice-durum wheat and rice-barley cropping systems in the surface soil and at the depth of 15-30 cm. At the same time, at the depth of 30-45 cm, rice-barley cropping system exhibited statistically lower availability of P in comparison to other cropping systems. Similar,

decrement in available P along soil depth was reported by Meena and Biswas (2014) in wheat-soybean cropping system. After rice crop harvest, no significant effect of any cropping system on phosphorus availability of soil in the 15-30 cm soil layer was found. But after harvesting of rice crop at the depth of 30-45 cm, soil available P was significantly greater in rice lentil cropping system in comparison to the other three cropping systems. Greater P availability in general in rice-legume systems may be attributed to the activity of *Rhizobia*, which are also reported to act as P solubilisers. Antoun *et al*. (2004) observed that 54% of the 266 species of *Rhizobia* obtained from the culture collections of different laboratories were able to solubilize dicalcium phosphates. Out of 446 strains of *Rhizobia* isolated from legume fields in different parts of Iran, 44% were able to solubilize tricalcium phosphate and 76% mineralized inositol hexaphosphate (Alikhani *et al*, 2006). However, these effects did not persist to the depth of 30-45 cm soil layer. At this depth in rice-barley cropping cropping significantly lower available P (9.94 kg ha^{-1} P) was found in comparison to other cropping system. This can be because of barley having higher root length so that it uptakes P from lower depth of soil. This also happened after harvesting of rice crops at the depth of 30-45 cm soil layer, which may also be due to the same reason. Growing a pulse crop after wet season rice can effectively utilize residual soil moisture, and reasonable scientific interventions and refinements, like drip irrigation along with soil moisture conservation avoids short-term tie-up of P (Adderley *et al*., 2006).

The interaction of fertigation regimes and cropping systems produced significant differences in P availability of various treatment combinations at a depth of 30-45 cm before the establishment of rice crop and at all depths after the harvest of rice crop. Growing a pulse crop after wet season rice can effectively utilize residual soil moisture, and reasonable scientific interventions and refinements, like drip irrigation along with soil moisture conservation avoids

short-term tie-up of P (Adderley *et al*., 2006). Wet to saturation in soil under W_3 compared to W_2 and W_1 may favour P losses from surface soil and its deposition in sub-surface soil (Ulen *et al*., 2012; Jian *et al*., 2016). Nearly, similar significant results of available P content were found after harvesting of rice crop. Besides this various workers found that wheat yield responses on low- and medium-P soils were directly proportional to the total available water supply and varied as a result of intermittent soil moisture stress (Boatwright *et al*., 1964; Power *et al*., 1961).

5.4.4 Effect of fertigation regimes and rice based cropping systems on soil available potassium

Table 4.10 shows that the ammonium acetate extractable K, expressed as potash, was statistically similar across various fertigation regimes and cropping systems before rice crop establishment as well as after the harvest of the rice crop at all depths except at the depth of 15-30 cm and 30-45 cm before rice crop establishment. Before rice crop establishment at the depth of 15-30 cm, the minimum potash availability was in W_1 followed by that in W_3 and maximum in W_2. On an average, potash availability in the experimental plot was found to exhibit an increasing trend with depth. This can result because of leaching of potash in the soil that belonged to the textural class of sandy clay loam. No differences in mineralogy of soil with depth are expected as there is little difference in the soil composition in terms of various soil separates and the soil in the 0-15 cm, 15-30 cm and 30-45 cm belonged to sandy clay loam textural class. Leaching of potash down the profile could be a possible reason for reduced availability of potash at the depth of 15-30 cm under W_1 fertigation regime, which is expected to leach least potash due to lowest amount of irrigation application during the *rabi* season.

At the depth of 30-45 cm soil before rice establishment, the availability of potash was significantly higher in W_2 and W_1 fertigation regimes and lowest in W_3 fertigation regime. The interaction of fertigation regimes and cropping systems resulted in significant differences in potash availability across various treatment combinations at the depth of 30-45 cm before the establishment of rice crop and at the depths of 0-15 cm and 30-45 cm after the harvest of rice crop. Sharma and Sharma (2013) reported that in general, the K leaching in presence of the accompanying anions followed the order of $SO_4^{2-} \leq H_2PO_4^{2-} < NO_3^- = Cl^-$. Highest CH_3COONH_4-extractable K (1 mol L^{-1}) was retained when K was applied along with $SO4^{2-}$ and $H_2PO_4^-$ anions, and the least was retained when accompanying anion was Cl^-. The influence of anions was more pronounced in the light textured soil and at high amounts of K application. The available soil K varied from 86.02 kg/ha to 117.82 kg ha^{-1} with a mean of 96.28 kg ha^{-1} before growing of rice and varied from 80.19 to 107.97 kg ha^{-1} with a mean of 87.55 kg ha^{-1} after harvesting of rice for surface soil with 0-15 cm soil depth (Table 4.10). This suggest the depletion of soil K after rice crop even with the application of K with same levels in all plots. Similar depletion of soil K was also found in mid-surface (15-30 cm) from 86.02 to 120.96 kg ha^{-1}, subsurface (30-45 cm) from 107.97 to 158.14 kg ha^{-1} before rice crop establishment and from 100.80 to124.99 kg/ha in mid surface and from 111.55 to 139.78 kg/ha in subsurface before and after cultivation of rice, respectively. Overall, soil K increased with increasing soil depth. Increase in soil K availability with depth might be due to leaching of K from surface layer due to heavy rainfall. Apart from that water table of that area is quite higher so there may be a chance of capillary fringe of ground water. That accumulates higher amount of K at 30-45 cm depth of soil. In 0-15 cm soil depth K availability was very low, but K availability increases with depth. The removal of potassium (K) by crops and its losses through leaching far exceeds the small

additions through fertilizers and manures which should not be long-term sustainable for yields of major cropping systems (Singh and Singh, 2003). Application of K fertilizers to fulfilling the crops need is not an established package of practice as Govt. is reluctant to subsidy on K fertilizers compared to nitrogenous fertilizes. So, K nutrition in soils is an important for correcting its deficiency, if any. Soil analysis after the harvesting of both *kharif* and *rabi* crop, depicted the deficiency of K along depth based as usual recommendation of soil available K (120 kg ha^{-1}) by Indian Soil Testing Laboratories (Nayyar and Sudhir, 2012). Similar type of K deficiency in soils also reported by Basak *et al*. (2016) and Biswas *et al*. (2017) in Indo-Gangetic plains. Overall soil data depicted a marginal increment in K content after harvesting of rice up to 116.3 kg ha^{-1}compared to that after harvesting of *rabi* crops at 110.5 kg ha^{-1} (Table 4.10). Retarded respiration rates of roots under wet to anaerobic soil conditions (Mandal *et al*., 2008) in rainy season ensure marginally higher quantity of K in soil. Additionally, application of nitrogen increased potassium uptake (Tandon and Sekhon, 1988). Furthermore, increment in soil depth increased available K along depth. Leaching losses of soluble K by N fertigation in rice season and in line drip irrigation in *kharif* crops may facilitate deposition of K in lower depths (Singh and Singh, 2003; Tandon and Sekhon, 1988). However, Meena and Biswas (2014) reported slight decreasing values of soil K along depth in soybean-wheat cropping system in *Inceptisols,* available K resided above the deficit level of soil test values. Cropping systems may have insignificant impact on available K content in soil due to deficiency or near critical stages of K in soil. Apart from that, various fertigation regimes were significantly influenced by available K. Before rice establishment at the depth of 0-15 cm W_2 fertigation regimes was significantly higher than W_1 and W_3 fertigation regimes. It may be due to higher amount of accumulation of available K with moderate amount of irrigation water in soil and at the depth of

30-45 cm soil layer W_2 and W_1 fertigation regimes was significantly higher than W_3 fertigation regimes which might be due to the same reason. Higher content of available K at sub surface layer (30-45 cm) may be due to large quantities of nitrogen used in rice-durum wheat cropping system which encourage crop uptake of nitrogen and potassium from upper layer and in turn heavy depletion of soil potassium (Singh *et al*., 2003) at the depth of 0-15 cm layer and increase available K at lower depth. Application of nitrogen and phosphorus resulted in 145% increase in potassium uptake as compared to control (Tandon and Sekhon, 1988). On coarse textured soils, split application of fertilizer potassium in both rice and wheat may give higher nutrient use efficiency than its single application due to reduction in leaching losses and luxury consumption of potassium (Tandon and Sekhon, 1988). This merits considering K application through fertigation along with nitrogen in split doses.

5.5 Effect of fertigation regimes and rice based cropping systems on nutrient uptake by rice

5.5.1 Effect of fertigation regimes and rice based cropping systems on nitrogen content and uptake by rice

N content in rice straw ranged from 0.64-0.93% in straw and 1.01-1.37% in grain. Nitrogen content in straw and grain was higher in systems where rice was followed by a cereal in comparison to the rice legume cropping systems due to higher amount of available and applied nitrogen during *rabi* season in rice cereal based cropping systems. Nitrogen uptake in rice grains was found to be significantly greater in rice-durum wheat cropping system in comparison to other cropping systems. Among various fertigation regimes, W_2 and W_3 fertigation regimes resulted in significantly greater nitrogen uptake in rice grains in comparison to W_1 fertigation regime.This may be due to higher application of nitrogenous fertilizer through drip line in W_2

and W_3 fertigation regimes (40 and 60 kg/ha N respectively). Besides this grain yield of these two fertigation regimes was also significantly higher than W_1 fertigation regimes.

5.5.2 Effect of fertigation regimes and rice based cropping systems on phosphorus content and uptake by rice

A perusal of table 4.12 suggests that P content and uptake in rice straw was significantly affected by fertigation and cropping systems. This could have resulted because of varying N availability across various cropping systems as well as fertigation regimes which have resulted in differential P uptake. P content was found to be significantly lower in W_2 in comparison to W_1 and W_3, which was also probably related with N availability and uptake. The content and uptake of P in rice straw was found to be significantly higher in rice-durum wheat cropping system in comparison to other cropping systems. A probable reason for this phenomenon could also be associated effects of nitrogen availability. A significant interaction of fertigation regimes and cropping systems was found in terms of the P content and uptake by straw under various treatment combinations. P content and uptake in rice grains was found to be statistically similar across various fertigation regimes. Phosphorus being mobile in plants, the differences in P uptake would have been prominent during the times of fertilizer application or soon after that. The content of P in rice grains was found to be significantly higher in rice-lentil cropping system in comparison to rice-barley and rice-chickpea cropping systems. The uptake of P in rice grains was found to be significantly higher in rice-lentil and rice wheat cropping systems in comparison to rice-chickpea and rice-barley cropping systems. This could have resulted because of greater P solubilization by the *Rhizobia* in symbiosis with the preceding legume crops. This reason could also have resulted in total P uptake by rice crop being significantly higher in rice-lentil and rice-wheat cropping systems in comparison to rice-chickpea and rice-barley cropping systems. Wang

et al., 2017 reported that P concentration and accumulation increased with the application of P fertilizer, in low P (i.e., no P) and high P (i.e., 40 & 60 kg/ha P) total P accumulation by rice crop increased by 14% on average; however, the straw and grain P accumulations increased by 29% and 3%, respectively. The average whole plant P concentration increased by 12%; however, the straw and grain P concentrations increased by 26% and 2%, respectively, similar results have been reported in case of wheat and rice (Akhtar *et al*., 2011).

5.5.3 Effect of fertigation regimes and rice based cropping systems on potassium content and uptake by rice.

K content in rice straw was found to be significantly more in rice-durum wheat cropping system than the other three cropping systems (Table 4.13). This may be because in rice-durum wheat based cropping system there is application of MOP in both *rabi* and *kharif* season in comparison to rice-legume cropping systems where MOP is applied only to the rice crop. As discussed in section 5.4.4 above, a substantial portion of applied potash gets leached down the profile to sub soil layers. Sharma and Sharma (2013) reported that higher levels of K application result in higher losses of K, especially in sandy loam soil as observed from the leachate concentration. They further found that among the different K sources, the maximum amount of K leaching was noticed in the soil column amended with KCl. Thus there is a likelihood of K getting leached into the subsoil layers in rice-durum wheat cropping system, where K was applied as MOP and at far higher rates than in the rice-legume systems. Thus, higher leaching losses promoted greater K content in subsoil layers in rice-durum wheat cropping system, which further provided an opportunity for greater K availability, albeit in sub soil layers, resulting in greater K content in rice grown in this system in comparison to other rice based systems.

5.6 Effect of fertigation regimes and rice based cropping systems on various nutrient use efficiency indices

5.6.1 Effect of fertigation regimes and rice based cropping systems on internal nutrient use efficiency

No significant effect of various fertigation regimes were observed on internal N use efficiency of rice plants. Rajput (2010) showed that NUE in fertigation was 95% whereas broadcast fertilizer produced 40% and he also speculated that higher NUE in fertigation over broadcast fertilizer due to proper dose and time of fertilizer application. The internal use efficiency under various fertigation regimes were found to vary between 41 and 43 per cent for nitrogen, between 175 to 204 per cent for phosphorus and between 33 to 39 per cent for potassium. Similarly, the internal use efficiency under various cropping systems was found to vary between 41-44 per cent for nitrogen, between 176 to 211 per cent for phosphorus and between 33 to 35 per cent for potassium. A significant effect of cropping systems on the internal nutrient use efficiency of P was observed. Rice-barley cropping system had significantly greater internal phosphorus use efficiency than the other three cropping systems. The P use efficiency for biomass production is equivalent to the reciprocal of the P concentration for the entire crop (Ahmad *et al*., 2001; Peng, 2011). Vandamme *et al*. (2016) reported that the total P concentration in straw and grain of rice was 0.5 per cent, so the low P concentration has been considered as a key trait for improving the P efficiency of a system via reduced P removal with crop. In their study, P concentrations in grain and straw were influenced by PUE. Additionally, in comparison with the grain P concentration, the straw P concentration was low. Their results suggested that the straw P concentration has a considerable influence on PUE in comparison with that of the grain P concentration, implying that with low straw P concentrations are likely to have high

PUE. In rice barley cropping system the overall P concentration was 0.45% (0.09% by straw and 0.36 % by grain).Probably for this reason the internal use efficiency of phosphorus was significantly higher in rice barley cropping system (210.86 kg/kg). This result is similar to the Vandamme *et al*. (2016) and Rose *et al*. (2010) study, where low grain P concentration was found. They hypothesized that this may be used to improve the P efficiency of cropping systems by minimizing P removal from fields.

5.6.2 Effect of fertigation regimes and rice based cropping systems on partialfactor productivity of applied nutrients

The partial factor productivity from applied nutrients is a useful measure of nutrient use efficiency because it provides an integrative index that quantifies total economic output relative to utilization of all nutrient resources in the system, including indigenous soil nutrients and nutrients from applied inputs (Cassman *et al*., 1996). The partial factor productivity of applied nutrients was significantly affected by fertigation regimes in case of N, P and K. The partial factor productivity of applied nitrogen was significantly greater under W_1 fertigation regime than the other two (Table 4.15). In case of phosphorus and potassium, it was significantly greater under W_2 and W_3 fertigation regimes in comparison to W_1. As discussed in section 5.1, the grain yields of rice were significantly lower in W_1 fertigation regime in comparison to W_2 and W_3 (Table 4.1) which indicates that significant response of applied nitrogen is being received up to 40 kg N ha^{-1}, when 2/3 of the N is applied as fertigation. Thus, in accordance with the law of diminishing returns, we expect the partial factor productivity of applied nitrogen to decrease in W_2 in comparison to W_1 but thereafter the same shall not be expected to be significantly different. In other words, the partial factor productivity of applied nitrogen was higher in W_1 than W_2 and W_3 by 41.41% and 58.56%. This indicates that decrease in nitrogen application is

possible up to $W_2$from W_3 fertigation regime. Chen *et al*. (2017) has reported that it is possible to reduce N application in 200 mm irrigation regimes without yield reduction and with saving in both labour and time.

For the nutrients phosphorus and potassium, the partial factor productivity of applied nutrients was significantly greater under W_2 and W_3 fertigation regimes as against W_1. This result is in compliance with the decreasing partial factor productivity of applied nitrogen with increase in fertigation levels keeping in consideration that the progressively increasing levels of fertigation have nitrogen as the variable nutrient applied @ 20, 40 and 60 kg ha^{-1} in W_1, W_2 and W_3 fertigation regimes respectively. With P and K levels remaining similar and yield responding to increase in N application, this is natural to have decreasing partial factor productivity of P and K till we have yield response to fertigation as well as there is an increment in partial factor productivity of applied nitrogen.

5.6.3 Effect of fertigation regimes and rice based cropping systems on nutrient harvest indices

Nitrogen and potassium harvest indices were not significantly affected by fertigation regimes or cropping system (table 4.16). However, the phosphorus harvest index was significantly affected by fertigation regimes as well as cropping systems. Phosphorus harvest index was significantly greater when N fertigation was given @ 40 kg ha^{-1} in comparison to when N fertigation rates were 20 and 60 Kg ha^{-1}. This is probably because P content and uptake in straw was significantly affected by fertigation but the P content and uptake in rice grains was not significantly influenced by fertigation and at the time the availability of phosphorus in soil before rice crop establishment had significant influences on cropping systems. Probably there have been interactions between fertigation regimes and cropping systems in deciding the P

uptake across various treatments resulting in significant interactive effects of fertigation and cropping systems on phosphorus availability in soil at various depths as observed after the harvest of the rice crop (Table 4.9). Phosphorus harvest index was significantly lower for rice-durum wheat cropping system in comparison to the other three cropping systems. This is probably related to the phosphorus availability in soil at 0-15 cm and 15-30 cm depth, which was significantly lower than the phosphorus availability in rice chickpea and rice-lentil cropping systems before rice crop establishment. The phosphorus harvest index was significantly greater for rice-lentil system in comparison to the other three cropping systems. This must also be related to the phosphorus availability in the soil which was significantly greater in rice-lentil cropping system in comparison to the rice barley and rice durum wheat cropping system (table 4.9). Phosphorus harvest index is dependent on P concentration of crop grain, straw and yield. Wang *et al*. (2017) in his correlation analysis indicated that low straw P concentrations might be partly attributed to high phosphorus harvest index values.

5.6.4 Effect of fertigation regimes and rice based cropping systems on Physiological Nutrient use efficiency

There was no significance effect of fertigation regimes and cropping systems on the physiological nitrogen use efficiency in the rice crop. The physiological phosphorus use efficiency of rice was significantly higher under W_2 and W_3 fertigation regimes than in W_1 fertigation regime. This is probably because of the response of dry matter yield to N fertigation. As the dry matter responded to fertigation but there were no changes in the P application levels with fertigation, we see the effect in terms of increased physiological use efficiency of phosphorus. The physiological phosphorus use efficiency of rice was significantly higher under rice-barley and rice-chickpea cropping systems in comparison to rice-durum wheat and rice-

lentil cropping systems. This has again relations with the availability of nitrogen in these treatments. Rice-lentil cropping system had significantly lower availability of nitrogen in the surface soil in comparison to other cropping systems as measured in samples drawn after the harvest of the rice crop (table 4.8).

The physiological potassium use efficiency of rice was significantly higher under W_1 fertigation regime and lower under W_2 and W_3 fertigation regimes. This could again be because of the response of dry matter yield to N fertigation. As the dry matter responded to fertigation but there were no change in the K application levels with fertigation, we see the effect in terms of increased physiological use efficiency of potassium. Moreover, under lower N application in W_1, there was lower total uptake of potassium and lower total dry matter production which led to the decrease in the physiological use efficiency of potassium.

Summary & Conclusion

Chapter-6

SUMMARY AND CONCLUSION

Rainfed lowlands of eastern India face the problem of low nutrient availability, absence of assured irrigation along with seasonal and erratic precipitation which deters farmers from growing a post rice crop in the dry season. Rice-fallow systems are a routine and are preferred in view of farmers finding more lucrative enterprises during the dry season. The need, however, is to increase the intensity and diversity of the rainfed rice-fallow areas for making agricultural enterprise more profitable. Technological interventions to promote judicious use of water and nutrient resources can promote intensification of these systems. Though water for irrigation is usually not available in these areas, water harvesting or ground water extraction can sometimes provide some critical life saving irrigation in these areas. In such a situation, there is merit in trying efficient water and nutrient delivery mechanisms such as drip or sprinkler systems. When such systems are used, there can be wider choices for post rice crops to be grown leading to an increase in the diversity of the cropping systems. Different rice based cropping systems as well as the effects of fertigation regimes may modify the root penetrability and soil physical conditions and hence the nutrient extraction by roots from various depths of the soil profile. The present investigation was carried out in an ongoing fertigation experiment initiated in June 2014 and laid out in a split plot design involving various fertigation regimes and rainfed rice based cropping systems at the farm of Bihar Agricultural College, Sabour. This is an account of an investigation involving field and laboratory studies conducted during the third rice crop in the system involving zero till direct seeded rice following cropping systems with zero till direct seeded durum wheat, barley, lentil and chickpea. The experiment involved three levels of fertigation in main plots involving nitrogen fertigation levels @ 20, 40 and 60 kg N ha^{-1} during

kharif season and corresponding levels of irrigation during the dry season at 200, 300 and 400 mm to the post rice crops.

Rice yields were significantly affected by the fertigation regimes but remained unaffected by the choice of the cropping systems. Accordingly, there were distinct influences of fertigation and cropping systems on ephemeral soil physical and chemical properties and nutrient relations in soils and plants. The soil profile penetration resistance measured before rice crop establishment using a cone penetrometer showed significant influences of fertigation regimes and cropping systems, but these differences did not persist till after the harvest of the rice crop. The steady state infiltration rate was found to be lower for the rice-legume cropping systems in comparison to the rice-durum wheat and rice-barley cropping systems. However, no significant effects of the treatments on bulk density were observed. Although cropping systems did not show any significant effects on maximum water holding capacity of the soils, it was significantly influenced by the fertigation regimes, being significantly greater under higher fertigation regimes when measured before rice crop establishment. The effect was short lived with no significant influences observed in measurements after the harvesting of the rice crop. There appears to be a role of the fertigation influenced wetting and drying cycles which marred the influence of fertigation regimes after the rice crop harvest. The effect of cropping system and fertigation regimes on water stable aggregates were not observable before rice crop establishment; however, by the time the rice crop was harvested, significant influences of fertigation regimes (*aka*. Nitrogen fertigation levels) were seen indicating significantly greater wet aggregate stability in plots receiving higher levels of nitrogen fertigation. Wet oxidisable carbon in surface and sub-surface soil samples drawn before rice crop establishment was not affected by fertigation regimes but significantly affected by cropping systems. Before rice crop establishment, rice-

chickpea cropping system demonstrated significantly lower organic carbon contents in comparison to the rice-durum wheat and rice-barley cropping systems, likely because of greater consumption of organic carbon by nitrogen fixing microorganisms in rice-chickpea cropping system. The effects were not found to persist till after the harvest of the rice crop. In the sub soil zones, *i.e*., at 15-30 cm and 30-45 cm soil depths, the available soil nitrogen content was significantly greater in treatments receiving less irrigation through fertigation during the *rabi* season, likely due to greater uptake of soil nitrogen with increasing water availability. After the harvest of the rice crop, the available N content at various depths was significantly lower in rice-chickpea cropping system followed by that in the rice-durum wheat cropping system and maximum in rice-barley cropping system. This may be due to substantially higher rates of nitrogen application in cereals than legumes. Before rice crop establishment, the average P availability was significantly higher in rice lentil cropping system than in rice chickpea cropping system, both of which had significantly higher P availability than rice-durum wheat and rice-barley cropping systems in the surface soil and at the depth of 15-30 cm. This may be due to the effect of symbiotic *Rhizobia*, which along with fixation of nitrogen, consume soil organic matter and solubilize phosphorus in the soils. Available K was found to be statistically similar across various fertigation regimes and cropping systems. N fertigation @ 60 kg ha^{-1} and 40 kg ha^{-1} demonstrated significantly greater nitrogen uptake by rice grains in comparison to 20 kg ha^{-1}. Whereas, P content in rice straw was found to be lower in 40 kg $ha^{-1}$and 60 kg ha^{-1} N fertigation compared to 20 kg ha^{-1} N fertigation. P uptake by rice grains was significantly greater in rice-lentil and rice-durum wheat cropping systems in comparison to rice-chickpea and rice-barley cropping systems. K content in rice straw was found to be significantly more in rice- durum wheat cropping system compared to rest three cropping systems. This can be due to low K

availability in rice durum-wheat cropping system than the other three cropping system after harvesting of rice. This may also be because in rice durum wheat cropping system there was application of potassic fertilizer (MOP) in both *rabi* and *kharif* seasons. The fertigation regimes and rice based cropping systems have also influenced various nutrient use efficiency indices. A significant effect of cropping systems on the internal nutrient use efficiency of P was observed as rice-barley cropping system had significantly greater internal phosphorus use efficiency than the other three cropping systems. The partial factor productivity of applied nutrients was significantly affected by fertigation regimes in case of N, P and K as N fertigation had a negative relation with the partial factor productivity of applied nitrogen but a positive relationship with the partial factor productivity of applied P and K. The phosphorus harvest index was significantly greater when N fertigation was given @ 40 kg ha^{-1} in comparison to when N fertigation rates were 20 and 60 Kg ha^{-1}. Phosphorus harvest index was significantly lower for rice-durum wheat cropping system in comparison to the other three cropping systems. The phosphorus harvest index was significantly greater for rice-lentil system in comparison to the other three cropping systems. The physiological phosphorus and potassium use efficiencies of rice were significantly higher under higher levels of N fertigation.

Based on the analysis of the salient findings and reasoning based on pre-existing literature, it appears that the fertigation levels and cropping systems do have significant influences on soil physical conditions and nutrient relations in soils and plants. Nutrient extraction from the soil profile also seems to have significant influences of fertigation regimes and cropping systems. Some influences are not long lasting but their ephemeral nature can be an indicator of the direction of changes expected in the long term. The decision of fertigation in rainfed rice based

ecologies should not only take into consideration the objectives of efficient water and nutrient delivery but also the ecosystem characteristics on a cropping systems basis.

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Appendix

APPENDIX –I

Summary of weather conditions prevailing during the *kharif* rice growing period of 2016 at Bihar Agricultural College, Sabour, represented as per the standard meteorological weeks. Maximum and minimum temperatures, relative humidity and wind speed are represented as the average values over the respective standard meteorological weeks where as the rainfall, bright sunshine hours and pan evaporation are given as the cumulative amount during the said standard meteorological week.

Standard met.week	Temperature (°C)		Relative Humidity (%)		Rainfall (mm)	Wind speed (km hr^{-1})	Bright sunshine hours (hrs)	Pan evaporation (mm)
	Max.	Min.	7:00 AM	2:00 PM				
18	36.66	22.06	76.71	51.00	0.00	08.44	28.60	51.00
19	37.03	22.86	87.00	45.43	23.40	08.30	37.20	39.50
20	34.91	23.64	84.57	56.86	0.00	12.63	43.90	32.30
21	34.51	24.33	85.29	61.14	4.80	08.14	35.20	31.80
22	33.43	23.04	86.86	63.14	77.80	07.79	53.80	23.40
23	35.87	26.20	80.57	58.29	3.40	08.86	55.30	40.00
24	34.61	24.86	85.71	71.86	49.00	08.10	32.10	29.20
25	32.03	25.10	88.43	77.14	63.80	08.00	33.70	26.60
26	33.41	26.29	83.43	72.43	0.00	06.51	41.80	29.20
27	30.39	25.09	94.43	85.14	204.10	09.70	23.10	11.20
28	32.90	25.86	88.86	76.14	43.40	08.57	36.60	13.40
29	30.86	25.40	89.29	84.71	40.90	07.07	12.60	07.00
30	32.96	25.23	88.43	76.14	21.40	08.39	16.50	07.70
31	33.10	25.71	86.57	73.57	1.40	08.79	57.80	22.80
32	32.16	25.63	89.00	77.71	36.50	11.31	35.20	19.00
33	31.50	25.94	83.57	79.29	25.50	09.49	41.20	18.00
34	32.31	25.13	87.00	73.71	7.00	08.61	49.00	24.80
35	33.11	26.60	88.00	74.86	8.20	06.70	41.50	19.90
36	31.01	24.69	91.57	83.29	139.10	05.51	30.00	07.00
37	31.71	25.51	88.86	75.43	10.00	06.80	17.30	08.40
38	31.43	24.17	89.57	81.43	51.40	05.37	36.50	13.00
39	30.21	23.73	89.57	80.57	112.20	05.76	28.70	13.20
40	32.51	25.21	85.86	75.86	25.60	03.30	55.90	19.30
41	31.20	23.31	91.00	75.14	5.60	04.03	36.20	10.00
42	31.94	20.07	88.71	60.00	0.00	01.83	54.50	14.50
43	30.91	19.54	89.29	63.14	0.00	01.93	47.60	10.60
44	30.83	18.24	89.86	63.43	0.00	02.37	57.10	16.40
45	30.26	15.99	86.71	59.86	0.00	02.41	41.10	16.70
46	29.09	12.94	92.14	49.00	0.00	02.24	48.40	13.80
47	27.64	12.21	92.14	50.43	0.00	01.79	24.40	08.40