PHYSICAL CHARACTERIZATION OF AN ACID ALFISOL UNDER MAIZE-WHEAT CROPPING AS INFLUENCED BY LONG-TERM USE OF CHEMICAL FERTILIZERS AND SOIL AMENDMENTS

THESIS

By

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IN

Partial fulfilment of the requirements for the degree

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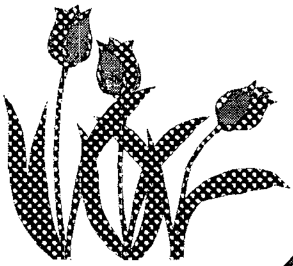

Is there anything I can say
anything I can give
or do for you ?
Because all that I am
all that I have
I owe to you ....

AFFECTIONATELY
DEDICATED TO MY
REVEREND PARENTS

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CERTIFICATE – I

This is to certify that the thesis entitled, "**Physical characterization of an acid alfisol under maize-wheat cropping as influenced by long-term use of chemical fertilizers and soil amendments**" submitted in partial fulfilment of the requirements for the award of the degree of **Doctor of Philosophy (Agriculture)** in the subject of **Soil Science** of Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya, Palampur, is a bonafide research work carried out by **Mr. Sudhir Verma** (Admission No. A-2002-40-14) son of **Sh. J. P. Verma** under my supervision and that no part of this thesis has been submitted for any other degree or diploma.

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

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Place : Palampur
Dated: 30th March, 2006

CERTIFICATE - II

This is to certify that the thesis entitled, **"Physical characterization of an acid alfisol under maize-wheat cropping as influenced by long-term use of chemical fertilizers and soil amendments"** submitted by **Sudhir Verma** (Admission No. A-2002-40-14) son of **Sh. J. P. Verma** to Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya, Palampur, in partial fulfilment of the requirements for the degree of **Doctor of Philosophy (Agriculture)** in the subject of **Soil Science**, has been approved by the Advisory Committee after an oral examination of the student in collaboration with an external examiner.

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I owe entire responsibility for all the errors and omissions.

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Place : Palampur
Date : 30th March, 2006

(Sudhir Verma)

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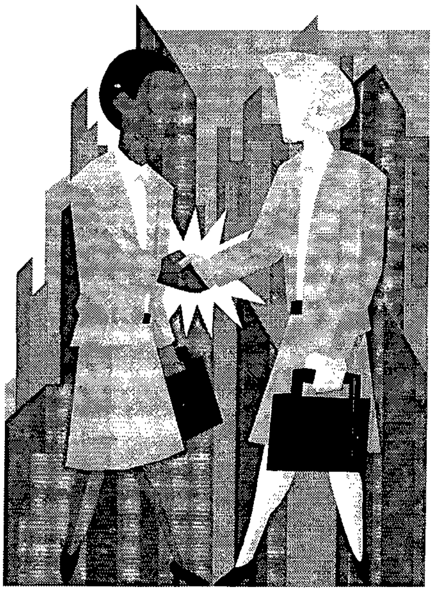


INTRODUCTION

Chapter I

Introduction

Maize-wheat is an important cropping sequence of Himachal Pradesh, contributing about 85 per cent of the total food grain production in the state. The average yield of these crops, however, is low, amounting to 1.61 and 1.52 t ha^{-1} against the national average of 1.64 and 2.62 t ha^{-1} for maize and wheat, respectively (Anonymous, 2004). Fertilizer application is an indispensable and integral part of modern intensive crop production systems to supplement soil nutrients removed by the crops. Due to the paucity of organic sources, the reliance of farmers on the inorganic fertilizers has increased. The fertilizer consumption in India during the last about five decades increased from 0.07 million tonnes (1950-51) to 16.8 million tonnes (2003-04). To sustain soil productivity, it is essential that plant nutrients are supplied in a balanced ratio. The present NPK use ratio in India is about 6.9:2.6:1.0 (Anonymous, 2004), as against the recommended ratio of 4:2:1. It shows the imbalanced use of the inorganic fertilizers. In Himachal Pradesh, however, the scenario is not as bad; the annual NPK use ratio (4.3:1.2:1.0) is nearly satisfactory. Nevertheless, the situation is disturbing when NPK use in the state is split over seasons. The NPK use ratio during *kharif* season is 20.5:1.9:1.0 and *rabi* season is 2.3:1.1:1.0 (Anonymous, 2004). Urea, which contributes to about 82 per cent of the nitrogen supplies, is the most commonly used fertilizer. Various reports have shown detrimental effects of continuous applications of inorganic fertilizers, and more so when applied in an imbalanced form, on soil health (Biswas *et al.*, 1971; Prasad *et al.*, 1983; Roszak *et al.*, 1990), but systematic studies have not been carried out.

An "All India Co-ordinated Research Project on Long-Term Fertilizer Experiments" was initiated at the CSK HPKV farm in 1972-73 (*rabi*) to investigate the effects of chemical fertilizers, alone or in combination with FYM and lime, on soil properties and crop yields in maize-wheat cropping sequence The use of chemical fertilizers alone declined the system (maize-wheat) productivity; however, when combined with FYM and lime, the system productivity was maintained. Continuous use of chemical fertilizers might have caused deterioration in physical, chemical and biological productivity of soil. Since the establishment of the experiment, much emphasis has been laid on yield performance and chemical properties of soil (Yaduvanshi, 1980; Kher, 1987; Sharma and Subehia, 1999; Verma *et al.*, 2005), the effect on soil physical productivity has, however, not received due attention (Acharya *et al.*, 1988).

The assessment of soil physical productivity in relation to crop production has remained a challenge. Measurement of few selected physical properties, as is usually done, may not serve the purpose of physical characterization of soils with respect to crop performance. The basic problem is that soil physical properties vary widely in time and space, and they are interdependent. It is not possible to change one property without affecting the other(s). Further, the effect of soil physical properties on crop growth is also interdependent. The influence of one property on crop growth may change if the other(s) property changes. It is, therefore, difficult to establish critical limit of each physical property in isolation in relation to crop growth. A single value soil physical index is required to characterize soil physical environment, which combines different soil physical properties directly and indirectly affecting crop growth. Letey (1985) proposed such an index, called the 'non-limiting water range' (NLWR) and it was successfully used by Sharma and Bhushan (2001) in characterizing a soil under rice-wheat cropping.

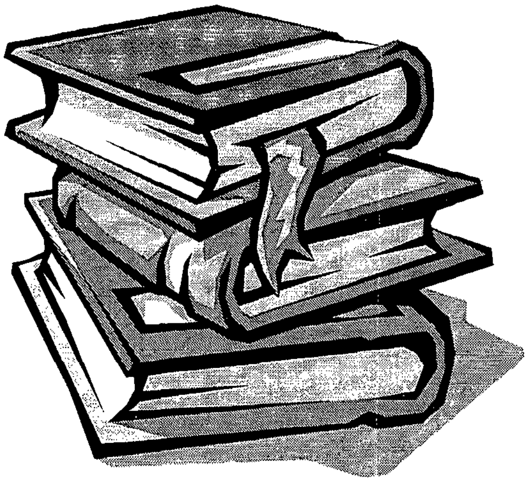
Factor productivity in agriculture over the last about three decades has shown a continuous decline. The land under agriculture is shrinking while demand for food is increasing. It has raised an issue of sustainability of agricultural production systems world over. Soil organic carbon dynamics is of paramount importance for sustaining soil quality and long-term productivity of agricultural systems. The loss of organic matter and the degradation of soil structure can have a deteriorating effect on the soil quality and crop productivity. Blair *et al.* (1995) introduced a concept of 'carbon management index' (CMI), based on changes in total carbon in the soil and its lability, to measure whether a system or a new management practice is sustainable in comparison to a more stable system.

Soil-water balance studies assume significance in efficient management of irrigation water. Most of the times, proper water budgeting is not possible because of lack of pertinent field data. Decision Support System for Agrotechnology Transfer (DSSAT) (Tsuji *et al.*, 1994, 1998), which has been used to evaluate irrigation strategies (Faria *et al.*, 1997) and regional crop water requirements (Heinmann *et al.*, 2002), provides an opportunity to estimate water budgeting based on soil, crop and weather parameters. The DSSAT is a software that describes crop growth, development and productivity as a function of weather variables, management practices and soil-water-nutrient dynamics.

The present study was planned to characterize the physical productivity of a soil under maize-wheat sequence as influenced by continuous use of chemical fertilizers alone or in combination with soil amendments (FYM and lime). The DSSAT model was also validated for soil-water balance. The objectives of the present investigation were as follows:

1. Investigation of soil physical properties under maize-wheat cropping as influenced by long-term use of inorganic fertilizers and soil amendments
2. Characterization of soil physical productivity under different treatments by using a single value index, the Non-Limiting Water Range (NLWR)
3. Validation of DSSAT (Decision Support System for Agrotechnology Transfer) model for soil-water balance under wheat in maize-wheat cropping sequence

4. Investigation of physical productivity of soils using NLWR under different cropping systems, with and without organic residue management, at the CSK HPKV, Palampur farm.



REVIEW
OF
LITERATURE

Chapter II

Review of Literature

The ability of soil to produce crops is dependent on chemical, physical and biological properties of soil. A proper balance of water-air-thermal regime in soil is a must for the most efficient use of available nutrients by the plants. Continuous use of organic and inorganic fertilizers and amendments (such as lime) are bound to influence soil properties, which in the long run may affect soil health and agricultural sustainability positively or negatively. Their effects on soil fertility and plant nutrition are well known, but effects on soil physical environment have often been questionable. Moreover, the physical characterization of soil, unlike chemical and biological characterization, has remained a challenge. The basic problem is the spatial and temporal variability of soil physical properties, and their interdependence among themselves and with respect to their effect on crop growth. It is therefore difficult, if not impossible, to establish a critical limit of each physical property in isolation in relation to crop growth. A single value soil physical index is required to characterize soil physical environment, which combines different soil physical properties affecting crop growth, directly or indirectly.

An attempt has been made in this chapter to compile the information available on the effect of fertilizers, manures and liming on physical properties of soil. The literature has been reviewed under the following heads:

2.1 Effect of chemical fertilizers on soil physical properties
  2.1.1 Aggregation
  2.1.2 Bulk density
  2.1.3 Porosity
  2.1.4 Water retention and availability
  2.1.5 Water movement

2.1.6 Soil strength
2.2 Effect of organic manures on soil physical properties
2.2.1 Aggregation
2.2.2 Bulk density
2.2.3 Porosity
2.2.4 Water retention and availability
2.2.5 Water movement
2.2.6 Soil strength
2.3 Effect of liming on soil physical properties
2.4 Physical characterization of soils
2.5 Sustainability of a crop production system
2.6 Field water balance

2.1 Effect of chemical fertilizers on soil physical properties

The major nutrients applied routinely as fertilizers to agricultural soils are nitrogen, phosphorus and potassium. The effects of chemical fertilizer applications on soil physical properties are complex and variable. Their application affects soil physical properties by influencing flocculation/dispersion phenomenon. Fertilizers improve crop yields, thereby increasing organic matter returns to soil. It favours build-up in soil organic carbon status and thus improvement in soil physical properties (Muthuvel *et al.*, 1982; Canarache *et al.*, 1984; Nambiar and Ghosh, 1984; Sheeba and Cheelamuthu, 2002). However, deleterious effects of chemical fertilizers on soil physical conditions have also been documented in literature (Biswas *et al.*, 1971; Prasad *et al.*, 1983; Roszak *et al.*, 1990). In general, the nitrogenous fertilizers have been linked with soil physical deterioration due to decline in pH, clay dispersion and adverse effects on soil micro-flora and fauna responsible for improving soil structure, while phosphatic and potassic fertilizers are associated with good soil structure. However, inconsistent results have been found in literature.

Melsted (1954) concluded that inadequate fertilization especially with respect to nitrogen was responsible for deterioration of soil health; to maximize crop production and minimize soil damage adequate supply of fertilizer nitrogen was essential. However, many studies have shown a deteriorating effect of the use of nitrogenous fertilizers on soil physical conditions (Fox *et al.*, 1952; Biswas and Ali, 1969; Biswas *et al.*, 1969, 1971; Prasad *et al.*, 1983; Kretinina, 1990; Singh *et al.*, 2002). Applications of NH_4^+-containing or forming fertilizers e.g. urea, ammonium sulphate [$(NH_4)_2SO_4$] and ammonium nitrate (NH_4NO_3), generally adversely affect soil structure. When conditions are unfavourable for nitrification (e.g. low pH, high levels of accumulated NH_4^+, low soil moisture content) NH_4^+ may accumulate in soil, and like Na^+, it favours dispersion of soil colloids and thus has a detrimental effect on physical conditions (Aldrich *et al.*, 1945; Fox *et al.*, 1952).

Phosphatic fertilizers have a beneficial effect in improving and maintaining physical condition and soil productivity. When water soluble phosphatic fertilizers are added to the soil, they get transformed immediately into a number of reaction products. Through these transformation reactions, phosphate anions play an important role in bonding of soil particles, and thus improving the physical conditions (Biswas, 1982). Addition of P to acid soils results in the precipitation of aluminium and iron as insoluble Al and Fe phosphates (Haynes, 1984). Yeoh and Oades (1981ab) found that when phosphoric acid is reacted with soils and clay minerals, the resulting precipitate of Al phosphates acts as a cement within the soil aggregates. Phosphates when used in conjunction with nitrogenous fertilizers play a very important role in checking the deleterious effects of nitrogenous fertilizers (Das *et al.*, 1966). Phosphate applications can also improve soil physical conditions by promoting increased top and root growth of plants and therefore increased organic matter (Haynes, 1984).

Potassium has also been associated with good soil structure. For example, K saturated soils have been found to have large aggregates and greater stability (Cecconi *et al.*, 1963) and thus good physical conditions. However, the effects of K are variable. Conflicting results relating to potassium (Levy and Torrento, 1995) conceal its behaviour. While, Grewal *et al.* (1999) reported a beneficial effect of K application on physical conditions, Biswas *et al.* (1969) observed a depressive effect of K application. Richards (1954) did not find any adverse effect of K on soil physical properties.

Fertilizer application in balanced form results in increased biomass and thus increased returns of organic material to the soil in the form of decaying roots, litter and crop residues, which plays an important role in improving physical conditions (Johnston, 1969; Canarache *et al.*, 1984; Chawla and Chabra, 1991; Schjonning *et al.*, 1994; Haynes and Naidu, 1998). However, Prasad *et al.* (1983) and Roszak *et al.* (1990) have reported adverse effect of fertilization. Intrawech *et al.* (1982) and Darusman *et al.* (1991), on the other hand, did not find any significant effect of long term application of NH_4^+ fertilizers, when added along with phosphatic and potassic fertilizers, on soil physical properties.

2.1.1 Aggregation

Soil structure is a dynamic property which can be defined as "the shape, size and spatial arrangement of individual soil particles and clusters of particles (aggregates)". Soil structure is generally characterized in terms of aggregate characteristics. Martin *et al.* (1955) defined soil aggregate as a "naturally occurring cluster or group of soil particles in which forces holding the particles together are much stronger than the forces between adjacent aggregates". Soil aggregates determine the air-water relationship and influence most of the soil physical properties and thus provide better environment for root development and plant growth.

Biswas and Ali (1969) showed adverse effect of ammonium sulphate on soil structure. Various other workers have reported adverse effect of nitrogenous fertilizers on soil aggregation and thus soil structure (Biswas *et al.,* 1969, 1971; Acharya *et al.,* 1988; Roszak *et al.*, 1990). Phosphate plays a definite role in building the structural status of soils through soil aggregation. Lutz *et al.* (1960) proved that phosphates themselves are responsible for the formation of soil aggregates. Biswas *et al.* (1969) observed that water stability of soil aggregates increased considerably due to the application of phosphatic fertilizers, while nitrogen had a slight depressive effect on soil aggregation. Potassium saturated soils have been found to have larger aggregates and greater stability (Cecconi *et al.,* 1963). Cruvinel *et al.* (1993) also observed large amount of potassium in the larger aggregate fractions in an oxisol. However, Aldrich and Martin (1954) and Biswas *et al.* (1969) indicated that potassium exerted a dispersing action on the soil.

Aldrich *et al.* (1945) observed that continuous application of ammonium sulphate resulted in pronounced depression in soil pH, inhibited nitrification and thus favoured accumulation of NH_4^+ in soil. This accumulation of NH_4^+ leads to dispersion of soil colloids. Kretinina (1990) observed a decrease in soil aggregation and aggregate stability due to accumulation of nitrogen. Similar dispersive effect of ammonium nitrate was reported by Fox *et al.* (1952). They found that low temperature inhibited nitrification and thus resulted in accumulation of NH_4^+ ions. Darusman *et al.* (1991) found significant increase in geometric mean diameter (GMD) of water stable aggregates (WSA) due to continuous application of a range of NH_4^+ fertilizers when phosphorus and potassium was also added. However, GMD decreased in subsurface layer. Myers and Thein (1991) reported destabilization of moist aggregates because of the dispersive action of NH_4^+ fertilizers $(NH_4)_2SO_4$ and NH_4Cl had a deteriorating effect on soil structure. NH_4Cl had a more deleterious effect than $(NH_4)_2SO_4$. This effect persisted even in the presence of phosphatic fertilizers. This deterioration in sandy loam soil was probably due to low content of clay (< 15%) and thereby possessing less buffering capacity (Chesters *et al.,* 1957; Biswas *et al.*, 1971).

Flocculation of soil colloids due to application of phosphorus was reported by Lutz *et al.* (1966). It was assigned to the precipitation of Al as insoluble Al-phosphates, which formed interstitial cement, binding aggregates together. Phosphate fertilization to berseem made a marked improvement in the structural status of an alluvial sandy loam soil (Biswas *et al.*, 1967; Pharande and Biswas, 1968). This has been attributed to better microbial activity and vigorous development of root system as a result of phosphate addition. Calcium as $CaSO_4$, a constituent of superphosphate may also take part in the mechanism of soil aggregation (Biswas *et al.*, 1969). Tattao and Amnart (1984) reported increased aggregation, under maize, mungbean and peanut, with the combined application of nitrogenous and phosphatic fertilizers. Similar improvement was observed by Nuttal *et al.* (1986) in their 25 year study on the Canadian prairies under continuous spring wheat.

Bhatia and Shukla (1982) after five years of fertilization to maize-wheat on a sandy loam soil observed an increase in water stable aggregates in comparison to control. Mishra and Sharma (1997) studied the effect of continuous application of fertilizers to a silt loam soil on aggregation. They found that after 10 years of continuous application of 100% NPK there was a significant increase in the fine and coarser aggregates over 50% NPK and unfertilized plots. The beneficial effect of balanced fertilizers on soil structure may be because of the role of phosphate ions in binding the soil particles or due to greater amount of organic residues produced in fertilized plots (Rabindra *et al.*, 1985). Prasad and Sinha (2000) also observed an increase in water stable aggregates (> 0.25 mm diameter) with the application of 50% NPK and 100% NPK over control. Similar findings were reported by Singh *et al.* (2002). They found improved aggregation with balanced nutrients and decrease in aggregation with nitrogen alone after 28 years of experiment with soybean-wheat-maize system. The proportion of undesirable cold fraction (>10 mm) decreased while desirable crumb fraction (0.25-10 mm) increased with the increase in fertilizer doses in a long term experiment (Toth *et al.,* 1997). Tiwari *et al.* (2000) found that MWD in plots receiving high doses of complete fertilizer (150% NPK) was at par with 100% NPK + farmyard manure.

However, Hadas and Quinton (1990) reported no effect of differential NPK treatments on water stability of soil structure. Wet aggregate stability was also found to be unaffected by NP treatments to wheat-barley over a period of 10 years (Biederbeck *et al.,* 1996).

On the other hand, Sinha *et al.* (1980) observed on a sandy loam soil under wheat-soybean-potato that WSA macro (> 2 mm) and micro (0.25-2 mm) decreased from 23.4 to 15.8 per cent and 35.5 to 22.1 per cent, respectively, with increase in dose of chemical fertilizers from 50% to 150% NPK. Roszak *et al.* (1990) from a nine year trial on black earth under cereals in rotation with grasses and legumes reported that fertilizers adversely affected soil structure. Kumar and Tripathi (1990) also observed a decline in mean weight diameter of aggregates in plots receiving 100% NPK in comparison to control. WSA (> 0.25 mm diameter) were 4-6% less in the plots receiving 100% NPK than under control. With respect to potassium, Biswas *et al.* (1970) observed an erratic behaviour on aggregation of different soils.

2.1.2 Bulk density

Various workers have found an increase in bulk density of plots where nitrogen was applied alone in comparison to control (Biswas *et al.,* 1971; Muthuvel *et al.,* 1982; Bhatnagar *et al.,* 1992; Singh *et al.,* 2002) which could be due to deterioration in structure. Tiwari *et* al. (2000) observed maximum bulk density (1.49 Mg m^{-3}) in plots receiving N alone. Zuzel *et al.* (1990), however, reported a decline in bulk density after 26 years with the application of NH_4NO_3 at 180 kg ha^{-1} N as compared to 45 kg ha^{-1} in a silt loam soil.

Phosphorus treated soils have been reported to have lower bulk density (Sharma *et al.* 1981; Muthuvel *et al.*, 1982). Lutz *et al.* (1960) observed that P treated plots were loose and easy to plough whereas control plots were hard and difficult to plough. Measurements confirmed that P treated plots had a lower bulk density. Yeoh and Oades (1981b) showed that WSA resulting from addition of phosphoric acid to soils led to lower bulk densities than untreated soils.

Bulk densities have been found to be lower with balanced fertilization (Acharya *et al.*, 1988; Amgain and Singh, 2001; Mishra and Sharma, 1997; Bhatnagar *et al.*, 1992; Singh *et al.*, 2002; Schjonning *et al.*, 1994). Tattao and Amnart (1984) and Miglierina *et al.* (2000) reported a decreased bulk density with the application of NP fertilizers compared to unfertilized plots due to production of high amounts of residues and a high proportion of large pores. Increasing nutrient elements (N, NP and NPK) or graded doses of NPK fertilizers (50% to 150%) showed lower bulk density than control after nine years of cultivation with rice-wheat-cowpea (Bhardwaj and Omanwar, 1992). After 15 years under soybean-wheat on a sandy loam soil, Bhatnagar *et al.* (1992) reported that fertilization with 100% NPK lowered bulk density as compared to the initial values, while imbalanced doses increased the bulk density.

Schjonning *et al.* (1994) investigated the effect of 90 years of cultivation and cropping in a rotation of winter cereals, root crops, spring cereals and grass/legume mixtures on soil properties. They observed that plots receiving annual application of NPK fertilizers had an 11 per cent higher organic carbon content than the control plots and bulk density decreased to 1.58 Mg m^{-3} from 1.64 Mg m^{-3} in the 0-20 cm soil layer. Obi and Ebo (1995) also reported a lower bulk density (1.50 g cm^{-3}) in comparison to control (1.54 g cm^{-3}) due to application of chemical fertilizers for two years to maize on an Ultisol. Continuous application of phosphatic and potassic fertilizers for 18 years to pearl millet-wheat rotation showed a decline in bulk density of surface soil (Grewal *et al.,* 1999). However, Prasad and Singh (1980), Intrawech *et al.* (1982), Darusman *et al.,* (1991), Prasad and Sinha (2000) and Sheeba and Kumaraswamy (2001) did not observe any significant effect of various chemical fertilizers on the bulk density of soil.

Some of the published literature has shown detrimental effect on bulk density even under balanced fertilization (Bhatia and Shukla, 1982; Sinha *et al.,* 1980; Biswas *et al.,* 1971; Prasad *et al.,* 1983; Bellaki and Badanur, 1997). This has been attributed to the deterioration in soil structure by nitrogenous fertilizers. Sinha *et al.* (1980) reported an increase in bulk density from 1.43 to 1.56 g cm^{-3} with increase in dose of NPK fertilizers from 50 to 150 per cent of optimum dose after six years under wheat-soybean-potato on a sandy loam soil.

2.1.3 Porosity

Soil porosity and pore-size distribution depends upon the soil aggregation and thus the structure of soil. Soil structure includes the creation of secondary coarser pores and the formation of intra-aggregate finer pores (Horn *et al.,* 1994). Structural degradation changes the pore size distribution and functionality, thus affecting soil air and water distribution and biological activity (Van Veen and Kuikman, 1990; Elliot and Cambardella, 1991; Hasink *et al.,* 1993), it is essential to have a high proportion of pores with capacity to retain water available to plant roots.

Kretinina (1990) observed a decrease in total porosity and soil aeration due to accumulation of nitrogen. However, total porosity increased significantly with application of NH_4NO_3 to maize (Marinari *et al.,* 2000). Addition of phosphoric acid to soil led to higher porosities due to improved aggregation and reduction in bulk density, than the untreated soil (Yeoh and Oades, 1981b). Schjonning *et al.* (1994) observed an increase in porosity from 38 per cent in control to 40 per cent with NPK application for 90 years.

Similar increase in porosity has been observed by various workers in different cropping systems (Bhatnagar *et al.*, 1992; Vennila and Muthuvel, 1998; Prasad and Sinha, 2000; Amgain and Singh, 2001). Obi and Ebo (1995) observed an increase in porosity from 41.5 per cent in control to 43.3 per cent with inorganic fertilization to maize in Nigeria. There was a significant increase in the proportion of large pores (>8.81 μm) in 0-0.07 m depth with fertilizer application in an Entic Haplustoll of Argentina under wheat-wheat and wheat-grass system for 15 years, due to residue accumulation and large root system (Miglierina *et al.*, 2000). However, Sheeba and Kumaraswamy (2001) did not observe any significant effect of fertilization on porosity.

2.1.4 Moisture retention and availability

Moisture retention and availability depends upon the soil structure and pore geometry of soil. At relatively low values of matric suction (between 0 and 100 kPa) the amount of water retained depends mainly upon the capillary force and pore size distribution and hence is strongly affected by the structure of the soil (Hillel, 1980). An increase in mean weight diameter (MWD) resulted in an increase in the water retained at 0.03 MPa and 0.1 MPa (Castro *et al.*, 1999).

Lutz *et al.* (1960) observed higher soil moisture content throughout the growing season in phosphorus treated plots. In laboratory studies, Lutz *et al.* (1966) showed that phosphorus additions favoured flocculation of soil colloids and increased the water holding capacity of the soils. Yeoh and Oades (1981b) observed higher water holding capacity due to addition of phosphoric acid. Similar effect of phosphate addition on soil moisture content and water retention characteristics due to improved aggregation have also been reported by Biswas *et al.* (1967, 1969).

Acharya *et al.* (1988) studied the effect of continuous application of chemical fertilizers on a silt loam soil cropped with maize-wheat. They found that soil water retention on mass basis was lowest with 100% N alone at all values of matric suction. Plant available water content was also lowest under 100% N. Except at saturation, N alone plots retained lower water than control. With the increase in level of balanced fertilization, amount of available water increased. Improved water retention characteristics with fertilization were also observed by Bhatnagar *et al.* (1992), Sheeba and Cheelamuthu (1996), Vennila and Muthuvel (1998), Prasad and Sinha (2000) and Amgain and Singh (2001). Higher profile moisture content in 85 cm deep profile after wheat harvest showed improvement in moisture retention due to continuous fertilization (Bhatnagar *et al.,* 1992). There was not much difference in water retention at permanent wilting point (Yadav and Kumar, 1993; Intrawech *et al.*, 1982; Acharya *et al.*, 1988; Darusman *et al.*, 1991; Amgain and Singh, 2001) as at this suction it is primarily dependent on texture and not structure.

Biswas *et al.* (1971), Bhatia and Shukla (1982), Obi and Ebo (1995), and Sheeba and Kumaraswamy (2001) did not observe any significant effect of continuous fertilizer additions on water retention and availability characteristics.

However, Sinha *et al.* (1980) reported a decrease in water holding capacity with high dose (150% NPK) of chemical fertilizers. From a nine year trial on black earth, Roszak *et al.* (1990) also observed that fertilizers adversely affected soil structure and thus water retention.

2.1.5 Water movement

Water transmission characteristics viz. infiltration rate and hydraulic conductivity, are affected by texture and structure. These will be higher, if the soil is highly porous, fractured or aggregated, than if it is highly compacted and dense (Horn *et al.*, 1994). A significant relationship was found between hydraulic conductivity and water stable aggregates >500 μm (Whitbread *et al.*, 2000). Hydraulic conductivity not only depends on the pore volume but also continuity of conducting pores.

Pillsbury (1947) found a significant reduction in infiltration rate following application of $(NH_4)_2SO_4$ to surface irrigated Californian soil, due to its effect on soil structure. The hydraulic conductivity of a sandy soil under maize-wheat increased due to application of fertilizers (Bhatia and Shukla, 1982). This has also been attributed to the effect of nitrogen. Acharya *et al.* (1988) also observed lowest infiltration rate in plots receiving only nitrogen on a silt loam soil. However, Zuzel *et al.* (1990) reported higher infiltration rate of 22 mm h^{-1} under high N (180 kg ha^{-1}) rate in comparison to 9 mm h^{-1} under low N (45 kg ha^{-1}) rate. Higher infiltration rate with continuous use of calcium ammonium nitrate (CAN) in a silty clay loam soil under maize-wheat were also observed by Ram *et al.* (1992).

Various studies have reported an improvement in infiltration rate and saturated hydraulic conductivity with use of phosphorus or balanced application of chemical fertilizers (Acharya *et al.*, 1988; Obi and Ebo, 1995; Mishra and Sharma, 1997; Vennila and Muthuvel, 1998; Grewal *et al.*, 1999; Prasad and Sinha, 2000).

Application of fertilizers improved water permeability as compared to control in a sodic soil (Chawla and Chhabra, 1991). Application of phosphorus along with nitrogen further increased the infiltration rate. Application of NPK resulted in maximum cumulative infiltration into the soil. Saturated hydraulic conductivity of surface soil increased from 0.4 mm d^{-1} in control to 2.09 mm d^{-1} when only N was applied and increased further when P or P and K were applied together with N (upto 6.22 mm d^{-1}). Differences were also reflected in the subsoil, though their absolute values decreased markedly. As these soils were highly deficient in available N, even N alone improved crop growth and thus more residues were left in the soil.

However, Bhatnagar *et al.* (1992) did not observe any effect of application of different chemical fertilizers either alone or in combination.

2.1.6 Soil strength

Phosphorus treated soils were found to be moist, loose and easy to plough in comparison to untreated ones, which were hard, dry and difficult to plough (Lutz *et al.*, 1960). Phosphoric acid reduced hardness of soils as measured by modules of rupture (Lutz and Pinto, 1965) and increased soil friability as measured by aggregate tensile strength (Utomo and Dexter, 1981). A decrease in soil penetration resistance (SPR) has been reported with the application of balanced doses of fertilizers (Obi and Ebo, 1995; Mishra and Sharma, 1997; Prasad and Sinha, 2000).

2.2 Effect of organic manures on soil physical properties

Applying organic manures for plant nutrient supply is a traditional agricultural practice. In addition to supplying nutrients, the applied manures are known to have beneficial effects on soil physical properties (Baver, 1935; Sharma and Bhushan, 2001; Bhushan and Sharma, 2002; Brady and Weil, 2002). Numerous studies in both temperate and tropical regions have shown that large increases in soil organic matter content can be achieved by adding organic manures and wastes to soils (Khaleel *et al.*, 1981; Sanchez *et al.*, 1989; Sharma *et al.*, 2002; Sharma *et al.*, 2003).

Johnston (1986) observed an exponential increase in organic carbon content when FYM was applied to an arable soil (cropped continuously with cereals) each year at 35 t ha^{-1} for about 140 years. It is now approaching a new equilibrium level at an amount over three times that of unfertilized plots. Sauerbeck (1982) showed that when a range of organic materials were added to soil, accumulation of soil organic carbon increased in the order green manure < straw < fresh FYM < composted FYM. When composted material is added to the soil it is relatively more resistant to further breakdown than fresh material. Increase in soil organic matter leads to enhanced soil microbial activity. Since soil organic matter content and soil biological activity increases when manures are applied to soils, it is not surprising that soil physical properties also typically improve (Sanchez *et al.*, 1989). The influence of organic matter on soil physical properties depends on amount and type of added organic materials (Nelson and Oades, 1998). Improvement in soil physical properties due to increase in soil organic matter have been reported by many workers (Baver, 1935; Khaleel *et al.*, 1981; Sharma and Bhushan, 2001; Bhushan and Sharma, 2002; Celik *et al.*, 2004). Organic matter had a loosening effect on soil (Albinet, 1971) and decreased surface crusting (Epstein *et al.*, 1976).

However, detrimental effects of adding large quantities of organic manures to soils have also been documented in literature. These include surface crusting, increased detachment by raindrops and decreased hydraulic conductivity (Cross *et al.*, 1973; Mazurak *et al.*, 1975; Olsen *et al.*, 1970; Tiarks *et al.*, 1974; Weil and Kroontje, 1979). The primary reason for this soil structural breakdown is the high content of monovalent cations (Na^+ and K^+) in animal waste material. In addition high concentrations of NH_4^+ may also accumulate through mineralization of organic waste nitrogen (Haynes and Naidu, 1998). Another problem sometimes noted at high rates of manure application is that soil can tend to take on water repellant properties (Olsen *et al.*, 1970). This is thought to be due to production of water repellant organic substances by fungi involved in decomposition of manure (Weil and Kroontje, 1979).

2.2.1 Aggregation

Many studies have shown an improvement in aggregation characteristics due to application of organic manures (Biswas *et al.*, 1969, 1971; Bhatia and Shukla, 1982; Kumar and Tripathi, 1990, Mathan, 1999, Prasad and Sinha, 2000; Barzegar *et al.*, 2002; Ram, 2000; Malo *et al.*, 2005).

Sinha *et al.* (1980) reported an increase in macro (> 2 mm) and micro (0.25-2 mm) water stable aggregates with the application of FYM along with 100% NPK.

Application of 100% NPK + FYM to paddy-wheat-cowpea for nine years increased the percentage of WSA (> 0.25 mm diameter) by 8 per cent over control (Kumar and Tripathi, 1990). MWD was also significantly higher than the other treatments.

Bhagat and Verma (1991) studied the impact of rice straw management and manure application on soil physical properties in a Typic Hapludalf under rice-wheat cropping. They found that the treatment of FYM and FYM + rice straw incorporation increased percentage of WSA (> 0.25 mm diameter) to 80.9 per cent and MWD to 0.82 mm from 69.7 per cent (WSA) and 0.61 mm (MWD) in control.

Kristaponyte (2001) determined that FYM at 40, 60 and 80 t ha^{-1} together with NPK fertilizers, increased soil structurality by 16.7 to 16.9 per cent, than in unfertilized treatments. Increase in WSA and MWD has also been observed with the application of FYM + 50% of recommended fertilizer dose (Bellaki and Badanur, 1997), FYM + blue green algae (Mishra and Sharma, 1997), green manure, wheat straw and wheat straw + green manure (Singh *et al.,* 2000), and FYM, wheat straw and composted bagasse (Barzegar *et al.,* 2002).

Tripathy and Singh (2004) carried out a study on a silty clay loam soil (Typic Haplustept) in New Delhi, India, to evaluate the effect of farmyard manure (FYM) vis-à-vis fertilizer and irrigation application on the soil organic C content and soil structure. The application of FYM and increasing N rate increased soil organic carbon content. Addition of FYM also increased the percentage of large sized water stable aggregates (>5 mm) and reduced the percentage of smaller size aggregates. This was reflected in an increase in the mean weight diameter (MWD) and improved soil structure. The organic C content in macro aggregates (>1 mm) was greater compared to micro aggregates, and it declined with decrease in size of micro aggregates. MWD was significantly correlated with the organic carbon content for the top two layers.

Loss in soil aggregation and soil organic carbon due to continuous cultivation has been observed (Ram, 2000; Malo *et al.*, 2005), however, original status of organic carbon was restored by 100% NPK + FYM (Ram, 2000). Improved aggregation due to application of organic manures has been attributed to the beneficial effect of certain polysaccharides formed during decomposition of organic residues by microbial activity, as well as the cementing action of bacteria and fungi themselves (Martin, 1945). Secretions of micro-organisms reduce the wettability of pore surfaces and thus increase the resistance to disaggregation by water (Le Villio *et al.*, 2002).

2.2.2 Bulk density

Organic matter has a loosening effect on soil (Albinet, 1971). Biswas *et al.* (1970, 1971) reported a significant negative relationship of bulk density and organic carbon content of soil. Organic manures increase organic matter content of soils, which due to its low bulk density and ability to increase soil aggregate stability results in lower soil bulk density (Dexter, 1988).

Bhatnagar *et al.* (1992) reported an 8.18 per cent decrease in bulk density under 100% NPK + FYM as compared to initial bulk density, after 15 years of cropping under soybean-wheat. Poultry manure application at 10 t ha^{-1} decreased the bulk density to 1.40 g cm^{-3} from 1.54 g cm^{-3} in control in an Ultisol under maize cultivation. Tiwari *et* al. (2000) recorded minimum bulk density of 1.20 Mg m^{-3} in 100% NPK + farmyard manure in comparison to 1.49 Mg m^{-3} in plots receiving N alone and control plots.

Ahuja *et al.* (2003) carried a study within an existing long-term dryland experiment at Colrado, to quantify the relationship between crop residue biomass generated by cropping system intensification and the physical properties of the surface soil (0-2.5-cm depth). They observed that bulk density was reduced by 0.01 g cm^{-3} for each 1000 kg ha^{-1} of residue addition over the 12-year period. Various other publications have showed similar effect of organic manures on bulk density (Acharya *et al.*, 1988; More, 1994; Bhagat and Verma, 1991; Nambiar, 1994; Moiseenko and Belous, 1997; Mathan, 1999; Prasad and Sinha, 2000; Bulluck *et al.*, 2002; Sharma *et al.*, 2003).

2.2.3 Porosity

Soil porosity was significantly higher in treatments receiving 100% NPK + FYM continuously for 15 years (Bhatnagar *et al.*, 1992). Porosity increased from 41.5 per cent under control to 45.3 per cent with the use of poultry manure (10 t ha^{-1}) for two years on an Ultisol under maize cultivation (Obi and Ebo, 1995). They observed a significant positive correlation ($r = 0.93$) between soil organic matter content and porosity. Marinari *et al.* (2000) reported from their study that soil total porosity increased significantly with the application of organics (compost and vermicompost) to maize crop in a sandy clay loam soil in Italy. Increase in total porosity has been attributed to increased number of pores in 30-50 and 50-500 μm size range and decrease in number of pores greater than 500 μm (Pagliai *et al.*, 1981).

Porosity increased by 7.1, 8.6 and 9.1 per cent with the application of FYM at 40, 60 and 80 t ha^{-1}, respectively, together with NPK fertilizers (Kristaponyte, 2001). Ahuja *et al.* (2003) observed from their study that residue addition over a 12-year period increased effective porosity by 0.3 per cent for each 1000 kg ha^{-1} of residue addition. Bhagat and Verma (1991), Ekwue (1992), Vennila and Muthuvel (1998), Prasad and Sinha (2000), Sheeba and Kumaraswamy (2001) and Barzegar *et al.* (2002) also observed an increase in porosity of soil due to the use of organic manures, either alone or in combination with recommended doses of fertilizers.

2.2.4 Water retention and availability

Increase in water holding capacity of soil due to application of manure has been observed due to increase in water retention at field capacity (Biswas *et al.*, 1969, 1971;

Khaleel *et al.*, 1981). Acharya *et al.* (1988) reported highest soil water retention and plant available water content in 100% NPK + FYM treated plots. This increase was particularly due to increase in moisture retention at low suctions. The structure and pore geometry of the soils play an important role in determining the water retention at low tensions, whereas water at high tensions is mostly retained on the external surface area of clay particles. Thus, little effect on water retention at permanent wilting point has been observed (Biswas *et al.*, 1969, 1971; Acharya *et al.*, 1988; Bhatnagar *et al.*, 1992; Barzegar *et al.*, 2002).

FYM application along with 100% NPK to rice-wheat-cowpea for nine years showed higher moisture content at -33 kPa and higher available water content due to higher organic matter content (Bhardwaj and Omanwar, 1992). Bhatnagar *et al.* (1992) observed from their experiment that 15 years of FYM + NPK application to soybean-wheat on a sandy loam soil increased water holding capacity by 32.3 per cent as compared to initial value and 34.26% with respect to control. Water retention at 0.33 bar suction showed an increase of 27.5% due to application of FYM + NPK. Addition of poultry manure (10 t ha^{-1}) significantly increased available water content (8.3 cm m^{-1}) as compared to control (7.5 cm m^{-1}) (Obi and Ebo, 1995). They found significant positive correlation of soil organic matter content with water retained at 0.33 bar tension (0.96) and available water content (0.96).

Mathur (1997) reported maximum field capacity moisture content (0.32 m^3 m^{-3}) under FYM plots. Application of FYM increased field capacity by 18.1 per cent over control. This may be due to decrease in non-capillary porosity and increase in total porosity due to FYM application. Moiseenko and Belous (1997) found an increase in capillary, hydroscopic and total water capacities of a sandy soil with long-term application of organic fertilizers. Wang and Yang (2002) after five years of cultivation of Egyptian clover-paddy-sesbania-maize on a clay loam soil found highly significant positive correlation between water content of surface soil layer at 1/30 MPa and organic carbon content in 1-2 mm and 0.5-1 mm fraction of surface soil. Various other studies have shown an increase in water retention and availability due to manure application (Doran, 1995; Mathan, 1999; Vennila and Muthuvel, 1998; Prasad and Sinha, 2000; Sharma and Gupta, 1998; Sheeba and Kumaraswamy, 2001).

2.2.5 Water movement

Improved water transmission has been observed with the addition of FYM (Biswas *et al.*, 1970; Acharya *et al.*, 1988). Bhatia and Shukla (1982) also showed decrease in hydraulic conductivity with FYM + NPK application in comparison to control in a sandy loam soil cropped with maize-wheat for five years. Obi and Ebo (1995) reported more than five fold increase in saturated hydraulic conductivity with the application of poultry manure (18.70 cm h^{-1}) in comparison to control (3.48 cm h^{-1}). Infiltration rate followed a similar trend. FYM application to cotton-wheat for eight years resulted in decrease in IR by 40.3 per cent over control in a sandy loam soil (Mathur, 1997). This has been attributed to decrease in non-capillary porosity. Use of organic soil amendments increased water infiltration rate due to enhanced soil aggregation (Stamatiadis *et al.*, 1999).

The increasing rates of organic materials (FYM, wheat straw and composted bagasse) from 0 to 15 Mg ha^{-1} to a loamy soil significantly influenced infiltration rate (Barzegar *et al.*, 2002). They reported higher Kostiakov-Lewis constants with increasing rates of organic materials. Higher 'a' constant indicates greater water intake into the soil. Saturated hydraulic conductivity of surface soil (0-10 cm) increased from 0.192 cm/h in N alone treatment to 0.416 cm h^{-1} in 100% NPK + farmyard manure (Tiwari *et al.*, 2000). Increase in water transmission characteristics with the use of organic manures has also been reported by Sharma *et al.* (1987), Badanur *et al.* (1990); Bhatnagar *et al.* (1992), Baldock *et al.* (1994), More (1994), Vennila and Muthuvel (1998), Prasad and Sinha

(2000), Ekwue (1992) and Patnaik *et al.* (1989) .

However, Tiarks *et al.* (1974) found that when cattle feed lot manure was applied to soil in spring at 90 to 360 t ha^{-1}, it caused decrease in hydraulic conductivity when measured in late summer due to structural breakdown by increase in concentration of monovalent cations, but leaching over winter reduced salt content to levels where there was no detrimental effect on soil physical conditions.

2.2.6 Soil strength

Addition of poultry manure (10 t ha-1) significantly decreased soil penetration resistance in comparison to control (Obi and Ebo, 1995). Mishra and Sharma (1997) reported that ten years of application of FYM (10 t ha-1) on a silt loam soil slightly decreased the SPR, however the decrease was non-significant. Application of 100% NPK + FYM for eight years decreased the SPR (Prasad and Sinha, 2000). Soil strength at 15 cm soil depth decreased to 2064 kPa in the stubble retained treatments from 2713 in the plots without stubble, with both treatments having similar water content at the time of measurement (Whitbread *et al.*, 2000).

2.3 Effect of liming on soil physical properties

The conventional aim of liming is to raise soil pH. This is considered to provide optimum conditions for crop growth. Contrasting results have been published with respect to the effects of liming on the physical properties of soils. Some workers have reported increased clay dispersion and reduced aggregate stability and infiltration rate with liming (Ghani *et al.*, 1955; Castro and Logan, 1991; Roth and Pavan, 1991), while others have observed that liming improved soil tilth and decreased surface cracking(Hoyt, 1981) and increased water holding capacity (Hoyt, 1981; Kohn, 1975) and aggregate stability of soils (Czeratzki, 1972). Dispersion and flocculation phenomenon are the important factors determining the effects of liming on soil physical properties (Sumner, 1992).

The contrasting results can be explained principally in the terms of (1) the short-term effects of liming on dispersion of soil colloids, (2) the flocculating and cementing actions of $CaCO_3$ and precipitated hydroxyl-Al polymers, and (3) the long-term effects of liming in stimulating crop growth, C returns to the soil and soil biological activity. In the short-term, liming may result in the dispersion of clay colloids and formation of surface crust. It happens due to the increase in soil pH, which results in the increased negative charge on clay colloids. Consequently, repulsive forces between particles dominate. Increased Ca^{++} concentrations and ionic strength in soil solution, due to prolonged liming or liming at higher rates, result in compression of electrical double layer and renewed flocculation of clay particles.

When present in sufficient quantities, both lime and hydroxyl Al polymers formed by precipitation of exchangeable-Al, can act as cementing agents bonding soil particles together and improving soil structure. Tama and El-Swaify (1978) reported that liming a Hawaiian soil from $pH_{(water)}$ 4.5 upto 6.0 resulted in increased clay dispersion and reduced infiltration rates. In sodic soils where high concentration of exchangeable and solution Na^+ favour dispersion, the addition of Ca^{++} as lime helps in promoting flocculation (Shainberg *et al.*, 1989).

Large lime application (e.g. 50 t ha^{-1}) are traditionally applied to temperate clay and loam soils used for continuous arable crop production in Europe (Davies and Payne, 1988). This is believed to make them easier to cultivate and work. Lime application significantly improved soil structure (Shanmuganathan and Oades, 1983) and infiltration rate (Miller, 1987).

Liming could well have indirect effects on soil physical properties through its effect on increasing crop growth and soil organic matter content. Liming can cause a large increase in the root and top growth and an increase in the returns of carbon to the soil in the form of dying roots and decaying crop residues. In the long run, these effects may well contribute to an improvement in soil structure (Haynes, 1984). Such effects have often been cited as a major cause of improvements in soil tilth measured following liming (Baver, 1956; Roth and Pavan, 1991).

Applied lime can also act as an amorphous cementing agent which can clog pores as well as physically bind adjacent particles together to form aggregates (Greene *et al.*, 1978; Rimmer and Greenland, 1976). Due to accumulation of $CaCO_3$ particles on the internal surfaces of soil pores, there is change in the colloid related activity as well as size and configuration of soil pores (Al-Ani and Dudas, 1988).

Addition of lime along with chemical fertilizers reduced bulk density as compared to control and increased water holding capacity (Sinha *et al.*, 1980; Prasad *et al.*, 1983). However, Acharya *et al.* (1988) observed that application of 100% NPK + lime for 13 years resulted in higher bulk density which may be attributed to the cementing effect of $CaCO_3$ precipitation. Lower infiltration further substantiated the cementation effect brought about by lime application.

Substantial increase in water retention of soil with increased lime levels has been observed (Patel *et al.*, 1992). Castro *et al.* (1999) reported an increase in aggregate stability. They found a significant linear correlation between MWD and calcium content and other indices affected by liming such as pH, sum of bases, base saturation and aluminium content. An increase in the stability indices (MWD) resulted in an increase in the water retained at 0.03 MPa and 0.1 MPa. Prasad *et al.* (1983) observed higher values of WHC of soil with the application of lime along with 100% N than in plots receiving 100% NPK or where no fertilizer was applied. Fine lime in soils would enhance the flocculation of clay particles and promote aggregation and swelling effect in the soils resulting in better soil structure and ultimately increased WHC of soils (Sairam, 1996).

2.4 Physical characterization of soils

Physical behaviour of soils have been evaluated on the basis of properties and physical processes, directly or indirectly related to plant growth, such as aggregation, aggregate stability, bulk density, porosity, water retention and transmission characteristics, etc. These properties have been related to crop yield (Biswas *et al.*, 1971; Taylor, 1971; Cannell, 1977; Jordan, 1983; Sharma and Aggarwal, 1984; Acharya *et al.,* 1988; Obi and Ebo, 1995; Bhushan and Sharma, 1997, 1999).

Among several indicators used to denote changes in soil by various management practices, structural indices like bulk density, aggregation and aggregate stability are used most frequently. Boekal (1963) and Low (1972) showed porosity to be a better structural index than the amount of water stable aggregates obtained by wet sieving. Pagliai and Vignozzi (2002) emphasized for soil porosity as an indicator of soil quality. But, measurement of few selected properties may not serve the purpose of physical characterization of soils with respect to crop performance. Soil physical properties vary widely in time and space, and they are interdependent (Letey, 1985; Ghildyal and Gupta, 2002).

Soil physical properties may be improved by adopting suitable tillage practices and incorporation of fertilizers and manures (Fagi and De Datta, 1983; Sharma *et al.*, 1995; Bhushan and Sharma, 2002), but their assessment in relation to crop growth has remained a challenge. Results drawn from correlating the measured physical properties with crop growth parameters and yields to work out the critical limits of individual soil parameters are highly site specific. It is very difficult to make out any general conclusion. A few attempts have been made towards characterizing the soils physically.

Gupta (1983) devised a criterion for physical rating of soils in relation to crop production. Product of eight soil physical properties, namely soil depth (A), bulk density

(B), moisture storage capacity (C), cumulative infiltration/apparent hydraulic conductivity (D), aggregation (E), non-capillary pore space (F), water table depth (G) and slope (H), have been used to compute a 'Physical Index' (PI). An appropriate weightage has been assigned to each component of PI for upland crops as well as for rice, which varies from one for the optimum range to a fraction for the others. The soils are classified into five categories based on the physical index to estimate their production potential, ranging from very suitable (PI > 0.90) to unsuitable (PI < 0.25).

Lal (1985) suggested a rating system to assess tillage requirements for diverse soil conditions in the tropics, to protect against soil degradation through soil erosion processes. Soil and climatic properties considered in developing the rating system include erosivitiy, erodibility, soil loss tolerance, compaction, soil temperature regime, available water holding capacity, cation exchange capacity, soil organic matter and crop residue on the soil surface at the time of seeding. The minimum and maximum cumulative rating values for all factors are 14 and 70, respectively. No till is applicable for soils with cumulative ratings of less than 30, and conventional tillage system of ploughing and harrowing is for soils whose cumulative rating values exceed 45. For soils with intermediate ratings some form of minimum or reduced tillage is suggested. Separate rating systems are suggested for rice and for tropical root crops.

Letey (1985) proposed a single value soil physical index called 'Non-Limiting Water Range' (NLWR) that combines different soil physical properties affecting crop growth directly and indirectly. The crop yields are, therefore, expected to correlate better with NLWR than the other commonly determined soil physical properties. The term 'Least Limiting Water Range' (LLWR) has also been used for NLWR (da Silva *et al.*, 1994). It describes a range in water contents, which incorporates limitations of water content on plant growth related to aeration, mechanical resistance and available water. In this moisture range water, aeration and mechanical resistance are not limiting for plant growth.

The NLWR represents the soil moisture range between two limits for plant growth – the aeration limit rather than the field capacity as the upper limit and the 'mechanical resistance' critical for root growth rather than the permanent wilting point (PWP) as the lower limit. The upper limit of NLWR could be the critical oxygen diffusion rate (ODR), 10% air filled porosity or moisture content at -10 kPa potential (Letey, 1985; da Silva *et al.,* 1994; Topp *et al.,* 1994; Carter *et al.,* 1999; Sharma and Bhushan, 2001). The lower limit is the mechanical resistance at which the root growth is reduced to about half. This value will vary with soil and crop. For wheat in medium textured soils, the critical mechanical impedance may be around 1.75-2.00 MPa (Taylor *et al.,* 1966; Carter *et al.,* 1999; Sharma and Bhushan, 2001).

It has been observed that the soil management practices, which result in an increased NLWR, can maximize the potential of a soil for crop production (da Silva and Kay, 1997b; Sharma and Bhushan, 2001; Benjamin *et al.,* 2003). da Silva and Kay (1997b) demonstrated that crop growing on soils which have a narrow LLWR are more vulnerable to both drought and high precipitation than those crops growing on soil which have a wide range. Topp *et al.* (1994) proposed NLWR: PAWC (Plant available water content) ratio as soil structure index and argued for its wider adaptability as the ratio was independent of soil texture.

LLWR was found to be more sensitive to changes in soil structure (characterized in terms of bulk density) than was available water (da Silva *et al.,* 1994). They observed that LLWR varied from 0-0.14 cm^3 cm^{-3} for the silty loam soil and from 0.05 to 0.13 cm^3 cm^{-3} for the loamy sand. At low bulk density, values of LLWR were higher for a silt loam than a loamy sand. At higher bulk density, LLWR was narrower and the relation between the soils reversed. da Silva and Kay (1997a) observed that LLWR was negatively related with clay and bulk density, and positively related with organic carbon content.

Hall *et al.* (1993) investigated the effect of gypsum application and deep ploughing with mould board (MB) plough on NLWR of soil cropped with wheat and forage crops. Gypsum substantially increased NLWR at a depth of 0.10 m (0.21 m^3 m^{-3}) as compared to soil without gypsum application (0.15 m^3 m^{-3}). No effect of ploughing was observed in the surface layer. However, deep MB ploughing greatly increased NLWR at 0.20 m depth to 0.15 m^3 m^{-3} as compared to 0.04 m^3 m^{-3} without deep MB ploughing.

While investigating the influence of tillage on LLWR, Betz *et al.* (1998) reported a decline in LLWR by 0.04 to 0.06 m^3 m^{-3} with no till. These results have been supported by the findings of Carter *et al.* (1999) and Tormena *et al.* (1999). Carter *et al.* (1999) used NLWR for physically characterizing a fine sandy loam soil under cereal cultivation with conservation tillage for a 12 year period. The NLWR under mould board ploughing and direct drilling was 0.133 and 0.061 cm^3 cm^{-3}, respectively. Correspondingly, the available water content under two situations was 0.186 and 0.177 cm^3 cm^{-3}. It reveals that based on classical concept of water availability, the two tillage systems were almost at par, but significant differences were observed when NLWR was used as soil physical index.

Tormena *et al.* (1999) evaluated LLWR in a Brazilian clay oxisol cropped with maize under no-tillage and conventional tillage. Results demonstrated that LLWR was higher in conventional tillage (0.096 cm^3 cm^{-3}) than in no-tillage (0.078 cm^3 cm^{-3}) and was negatively correlated with bulk density values above 1.02 g cm^{-3}. Lapen *et al.* (2004) found that no till soils were at greater risk of aeration limiting conditions. In all these studies, however, response of crops to NLWR has not been studied.

Sharma and Bhushan (2001) studied the effect of soil incorporation of Lantana biomass, an obnoxious weed, for 10 years on physical environment of silty clay loam soil under rice-wheat cropping. Lower soil water contents associated with 10% air filled porosity and greater soil water contents associated with a limiting penetration resistance of 2 MPa resulted in a lower NLWR (4.3%) for control as compared to lantana treated soil (7.4-15.1%). PAWC showed slight increase from 12.9 to 13.4-14.9% due to lantana additions. The NLWR: PAWC ratio was also lower in control (0.33) as compared to lantana treated soil (0.55-1.01). NLWR was significantly and positively correlated with wheat grain yield (r = 0.858**).

Benjamin *et al.* (2003) also reported a significant positive correlation ($r^2 = 0.76$) of LLWR with wheat yield under no-till system. They, however, found a poor correlation between LLWR and corn yield under dryland conditions. They proposed a term 'water stress day' (WSD), which was computed by summing the differences of actual water contents in the field from the limits identified by LLWR during the growing season. Significant correlation of corn yield with WSD was found.

da Silva and Kay (2004) have linked process capability analysis and LLWR for assessing physical quality. Capability analysis allows one to quantify process variability relative to given specifications. Temporal variability of soil water content generated individual values for soil water content inside the limits specified by LLWR. The natural process limits of the temporal variability in soil water content were computed from the mean and the standard deviation. They found that process capability parameter i.e. distance to nearest specifications (DNS) was related to clay and organic carbon contents.

2.5 Sustainability of a crop production system

Sustainability is the goal of most managed ecosystems. The operational meaning of sustainability is the ability of a system to maintain a certain well defined level of performance over time, without damaging the essential integrity of the system. Therefore, sustainability is a dynamic phenomenon. The goal of assessment of sustainability is to quantify the impact of management on soil properties and processes relevant to agronomic productivity and environmental quality (Lal, 1994). Soil quality is considered a key element of sustainable agriculture (Warkentin, 1995). Attributes of soil quality assessment have been outlined and described in several reports (Anonymous, 1992; Acton, 1993).

Soil management decisions often are aimed at improving or maintaining the soil in a productive condition, however various practices can have a detrimental impact on the sustainable productivity of soils. The complexity of agricultural systems and the wide range of possible management inputs require that soil quality be evaluated at individual management level (Carter *et al.*, 2004).

To assess the sustainability of soil, Lal (1994) suggested critical values of various indictors. Based on 'cumulative rating index' (CRI) of ten soil indictors, five categories from highly sustainable (CRI < 20) to unsustainable (CRI > 40) were given. Kaushal (2002) studied the sustainability of soil under maize-wheat cropping, based on the criteria given by Lal (1994). It was reported that plots receiving recommended dose of nitrogen alone for 29 years were rendered unsustainable. Unfertilized plots could still be sustained following integrated nutrient management. While, application of FYM or lime along with recommended dose of fertilizers helped in sustainable use of soil, those receiving 100% NP or 100% NPK could be sustained following high input system.

Soil organic matter (SOM) is considered to be a key attribute of soil quality (Larson and Pierce, 1991; Gregorich *et al.*, 1994; Bhattacharya *et al.*, 2000; Singh *et al.*, 2003) and thus is a major determinant of sustainability of agricultural systems (Carter, 2002; Blair *et al.*, 1995). Maintenance of SOM in agricultural soils is primarily governed by climate, particularly annual precipitation and temperature, and cropping practices (Jenny and Raychaudhuri, 1960). Amount and nature of soil organic carbon content play a key role in soil quality (Parr *et al.*, 1992). Soil organic carbon affects productivity through its effect on soil structure, plant available water capacity, as a source of plant nutrients and as a buffer against sudden fluctuations in soil characteristics. The loss of organic matter and the degradation of soil structure are responsible for the decline in productive potential (Cassel and Lal, 1992). Studies on soil organic carbon and dynamics are important for long term restoration of soil health and maximizing crop production. Therefore, measurements of SOC changes under various forms of management are needed for the development of sustainable systems. In addition to total soil organic carbon, it is also important to determine active fraction of carbon (Lal, 1994).

Small changes in total soil organic matter or carbon are difficult to detect because of large background levels and natural soil variability (Blair *et al.,* 1995; Carter, 2002). Attempts have been made to use sub pools of soil organic matter or carbon as more sensitive indicators of changes in pool size. Lefroy *et al.* (1993) proposed changes in the lability of soil carbon as a measure of sustainability. Labile soil organic matter attributes have been evaluated on their sensitivity to change in total soil organic matter (Campbell *et al.*, 1998; Biederbeck *et al.*, 1998; Bolinder *et al.*, 1999; Angers *et al.*, 1999).

The effect of chemical fertilizers alone, in balanced and unbalanced form, and when added along with organic manures on different pools of soil organic carbon have been reported by Singh *et al.* (2003). Balanced use of NPK fertilizer enhances the SOC restoration due to higher root biomass and rhizodeposition even under intensive cultivation, whereas no fertilization or imbalanced fertilization leads to negative impact on SOC restoration in long term land use crop management practices. Integrated use of NPK fertilizers along with manure further enhances this effect on SOC restoration. Continuous use of inorganic fertilizer N or NP alone could not improve active pools of carbon.

Blair *et al.* (1995) introduced the concept of 'carbon management index' (CMI).

They differentiated the soil organic matter pool into an active (labile carbon) and a stable fraction. The carbon management index, which is based on changes in total carbon in the soil and its lability, provides a sensitive measure of the rate of change in soil carbon dynamics of systems relative to a more stable reference soil.

Cultivation of soil in many cases results in the decline of total and labile fractions of soil carbon. Loss of labile carbon is of greater consequence than the loss of non-labile carbon. Saviozzi *et al.* (2001) observed a marked decline in total carbon and its various fractions due to continuous corn production for 45 days. Yang *et al.* (2005) reported a higher total organic carbon in paddy soil with fertilization over control and still higher with combined use of fertilizers and organic sources, especially under continuous water-logging. However, labile carbon was lower under waterlogged conditions in comparison to alternate wetting and drying, when chemical fertilizer and FYM was added.

Shrestha *et al.* (2002) conducted experiments in four farmers' fields in the Philippines utilizing a rice- (*Oryza sativa* L.) sweet pepper (*Capsicum annuum* L.) system aimed to determine the effects of different transition crops like indigo (*Indigofera tinctoria* L.), indigo plus mungbean (*Vigna radiata* L.) and corn (*Zea mays* L.) grown during the dry-to-wet (DTW) transition on total and labile C pools. The decrease in labile C with cropping ranged from 6% to 21% and increase with residue incorporation ranged from 18% to 37% at different sites, but total C remained unchanged. The labile C balance indicated a loss of up to 1,438 kg ha^{-1} due to farming practices and a gain of up to 3,077 kg ha^{-1} with residue addition. Catch crop residue management in intensive rice-based cropping systems can play a role in maintaining soil health, as indicated by the improvement in labile C. Labile C is sensitive to soil management practices, and thus provides a better measurement of C dynamics in the short to medium term than total C alone.

Continuous cropping resulted in a decline in carbon pool index (CPI), a greater decline in lability index and hence a decline in 'carbon management index'. Introduction of legume into a wheat cropping system restored CMI from 22 to 37. Data from Brazil showed no increase in total carbon with mulching but a 48% increase in CMI due to an increase in the lability of carbon in soil (Blair *et al.*, 1995).

Field trials, consisting of a legume followed by three wheat crops, were established on a degraded Ferric Luvisol (red earth) soil in New South Wales, to investigate the effect of crop residue and fertilizer management on wheat yield, soil physical properties and SOM. Total and labile C increased following a lucerne (*Medicago sativa* cv. Trifecta), however, chickpea (*Cicer arietinum* cv. Amethyst), barrel medic (*Medicago truncatula* cv. Sephi) and fallow leys resulted in no increases in soil C concentrations. During wheat the concentration of CL significantly increased on the treatments with wheat stubble retention. This resulted in the C Management Index (CMI) increasing from 19 to 27 (Whitbread *et al.*, 2000).

Continuous cultivation of rice-wheat along with lantana application on a silty clay loam soil significantly increased total carbon, labile carbon and other carbon indices of soil. CMI with lantana addition was 112.6 to 132.7 in comparison to 84.3 under control (Sharma *et al.*, 2003).

2.6 Field water balance

Increasing competition in water use has spurred the concept of better use and management of water resources. Therefore, it is necessary to study how water can be used efficiently (Molden, 1997). It is difficult to know the quantity of water that is really needed to grow crops because of the interrelationship of factors in the soil-plant-atmosphere system.

Water cycling in a cropped field can be characterized and quantified by a water balance, which is the computation of all water fluxes at the boundaries of the system under consideration. It is an itemized statement of all gains, losses and changes of water storage within a specified elementary volume of soil. Soil water balance studies assume significance in efficient management of irrigation water. Ritchie (1981a) laid emphasis on water balance studies because of its need for accurate estimation of crop yields, early warning about food shortages, better farm management, reliable irrigation scheduling and water resource planning, etc. Because of these urgent needs, it is important to develop models to estimate water balance.

Mathematical models, be it physically or empirically based, have the promising potential to explore solutions to water management problems. Evaluation of water management scenarios can be easily done, thus facilitating better recommendations for improved water use (MacRobert and Savage, 1998; Droogers and Kite, 1999; Droogers *et al.,* 2000).

Various processes involved in water balance dynamics, such as runoff, infiltration, percolation and soil water distribution in the unsaturated zone, can be simulated by models using Darcy's (Darcy, 1856) or Richards' (Richards, 1941) equations. These equations have been employed in different modes viz. WOFOST (Supit *et al.,* 1994), EPIC (Sharpley and Williams, 1990), CERES (Ritchie, 1998), SPASS (Wang and Engel, 2002), STICS (Brisson *et al.*, 2003), SWAP (van Dam *et al.*, 1997) and SIMULAT (Diekkrüger and Arning, 1995).

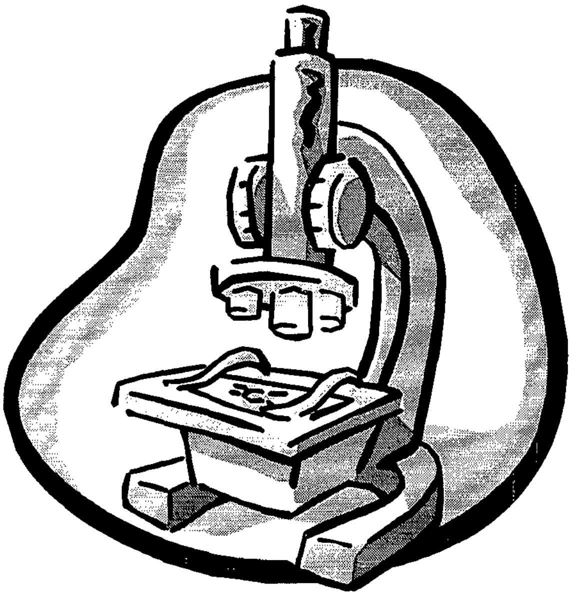
Among several available models, the crop growth models of 'Decision Support System for Agrotechnology Transfer' (DSSAT) system have been widely applied to many fields of application. DSSAT includes Crop Resource and Environment Synthesis (CERES), Crop Growth (CROPGRO) and other models which are linked to one soil water balance module (Tsuji *et al.,* 1994; Tsuji *et al.,* 1998). Satisfactory performances of the

CERES-wheat model have been observed under diverse set of environments (Otter-Nacke *et al.*, 1986; Bell and Fischer, 1994). Porter *et al.* (1993) compared three wheat simulation models AFRCWHEAT 2, CERES-wheat and SWHEAT for non-limiting conditions of crop growth in New Zealand, using two wheat varieties (Avalon and Rongotea). CERES-wheat predicted grain yields better than other models for cv. Avalon, but error was upto 29% for cv. Rongotea. A root growth subroutine from CERES-wheat model was tested by comparing actual and simulated root growth and distribution (Savin *et al.*, 1994). The model accurately predicted crop development and yield, but over-predicted root growth and under-estimated root weight. Bishnoi *et al.* (1996) observed that CERES-wheat predicted yield attributes close with 29th October and 13th November sowing dates, but deviation was higher with delayed sowing. The yield estimated with CERES-wheat was 85-94% of the observed with cv. HD-2329 in Punjab (Dhaliwal *et al.*, 1997). CERES-wheat model predicted the grain yield within a range of 12% for cultivar WH-592 at Hissar and HD-2329 at Jaipur and Ludhiana (Attri *et al.*, 1999). Ines *et al.* (2001) observed that DSSAT over-predicted the corn yield by about 7 q ha^{-1} in comparison to the observed yield of 53.1 a ha^{-1}. Kumar (2002) evaluated CERES-wheat in DSSAT v3.1 for varieties HS-240, HS-277, HPW-42, HPW-89 and VL-616 at Palampur, and reported that the model simulated phenological stages, dry matter accumulation in roots and grain yield with reasonable accuracy, but failed to simulate leaf, stem dry weight, yield attributes, straw yield, harvest index and N content and uptake. Faria and Bowen (2003) found that DSSAT v 3.5 under-predicted the bean crop yield. They ascribed it to under-estimation of plant water extraction by the model.

Soil water balance in DSSAT is based on Ritchie's model where the concept of drained upper limit and drained lower limit of soils is used as the basis of the available soil water (Ritchie, 1972; Ritchie, 1981a, Ritchie, 1981b). One dimensional soil water balance of a stratified profile is computed in a daily time step (Ritchie, 1998).

DSSAT has been used to evaluate irrigation strategies (Faria *et al.,* 1997) and regional crop water requirements (Heinmann *et al.,* 2002). Eitzinger *et al.* (2004) from their study on three different soils cropped to winter wheat and spring barley found that the simulated values of soil water content and grain yield lay in an acceptable range of ± 15 to 20 per cent compared with the data measured on a lysimeter. They found that the simulated evapotranspiration values were significantly higher than the measured ones, which could be due to deviations in the calculations of the front root velocity and soil water extraction as well as potential evapotranspiration.

However, Ines *et al.* (2001) concluded from their study on an acid sulphate soil that DSSAT has more empiricism in simulating the soil water balance and is therefore not generally applicable when soil moisture is an important parameter. In studies where water, oxygen and salt stress are important, SWAP is more preferable because DSSAT does not respond properly under extreme environmental stress where the effect of oxygen and salt stress to water uptake are not simulated by the model. DSSAT under estimated the evapotranspiration during the peak of growth when the canopy covers most of the soil. As a result of full grown height of crops the aerodynamic resistance is small thus increasing the flow of water in the canopy-atmosphere interface. The model overestimated the evapotranspiration when the crops were small, because the aerodynamic resistance was under estimated in the appraoch. Faria and Bowen (2003) evaluated the performance of soil water balance module (SWBM) in the models of DSSAT v3.5 against moisture data measured in bare soil and dry bean plots in Brazil. SWBM of DSSAT v3.5 showed a low performance to simulate soil moisture profiles. They attributed it to the inadequacies in the methods used to calculate soil water flux and root water absorption.



MATERIALS AND METHODS

Chapter III

Materials and Methods

The present investigation entitled, "Physical characterization of an acid Alfisol under maize-wheat cropping as influenced by long-term use of chemical fertilizers and soil *amendments" was carried out during 2003-04 and 2004-05 in an ongoing long-term field* experiment with maize (*Zea mays*)- wheat (*Triticum aestivum* L) cropping sequence. The experiment was established during 1972-73 *rabi* season at the experimental farm of College of Agriculture, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur (HP), India.

The details of the field experiment and the methodology adopted in carrying out the experimental work are described in this chapter under the following heads:

3.1 General description of the study area
  3.1.1 Location
  3.1.2 Climate
  3.1.3 Soils
3.2 Experimental details
  A. Study I: Long-term impact of organic and inorganic fertilizers and amendments on soil physical properties under maize-wheat cropping.
    3.2.1 Characterization of experimental soil
    3.2.2 Soil chemical and physico-chemical properties
    3.2.3 Soil physical properties
      I. Particle-size distribution
      II. Particle density
      III. Structural properties
      IV. Hydraulic properties
      V. Mechanical properties
    3.2.4 Field water balance
    3.2.5 Crop yields

B. Study II: Soil physical characterization and carbon management index under different long-term cropping systems with and/or without organic amendments.
    3.2.6 Non-limiting water range (NLWR)
    3.2.7 Carbon management index (CMI)

3.3 Meteorological parameters

3.4 Statistical analysis

3.1 General description of the study area

3.1.1 Location

The experiment was conducted at the Experimental Farm of the Department of Soil Science, CSK HPKV, Palampur (H.P). The experimental site is situated at $32^0 6'$ N latitude and $76^0 3'$ E longitude at an elevation of about 1290 m above mean sea level. The area lies in Palam Valley of Kangra district in the foothills of Dhauladhar range and represents the high rainfall mid-hill wet-temperate zone of Himachal Pradesh in North-West Himalayas.

3.1.2 Climate

The climate of the experimental site is wet temperate with mild summers (March to June) and cool winters. The experimental site represents high rainfall area (rainfall $\geqslant$ 1,500 mm) of Himachal Pradesh, covering about 15 per cent (8,900 km^2) of the total geographical area of the state. The mean annual rainfall (1974-2004) around Palampur is about 2,312 $\pm$ 618 mm. A major portion of the rainfall i.e. about 75 per cent is received during monsoon period from June to September. Winter rains (December to February) are meager and erratic. The mean rainfall (1974-2004) during the *kharif* (June to October) and *rabi* (November to May) is about 1,803 $\pm$ 519 and 509 $\pm$ 231 mm, respectively. The annual mean maximum temperature is about 23.2 $\pm$ 0.8 ^{0}C. May and June are the hottest months with a mean maximum temperature of 29.7 $\pm$ 1.7 ^{0}C. The annual mean minimum temperature is about 13.4 $\pm$ 0.5 ^{0}C. December to February is the coldest period. The minimum and maximum mean temperature during the coldest month of January is 5.0 ± 0.9 and 15.1 ± 1.4 ^{0}C, respectively. The soil temperature drops to as low as 2 ^{0}C during the winters and frost incidences are common. The mean monthly rainfall, evaporation and air temperatures at Palampur (HP) for the period 1974-2004 are illustrated graphically in Fig. 3.1 (Appendix-I). The important meteorological observations (weekly averages) for the period of investigation are also presented in Fig. 3.2 and 3.3 (Appendix-II and III).

3.1.3 Soils

The experimental soil is silty loam in texture and classified as Typic Hapludalf (Verma, 1979) as per the taxonomic system of soil classification (Soil Survey Staff, 1975), and Gray Brown Podzol according to the Genetic System of Classification. The soils in the region owe their origin to the fluvio-glacial parent material developed from rocks like slate, phyllites, quartzites, schists and gneisses. The soils are acidic in reaction (pH 5.2 to 6.2).

3.2 Experimental details

Two sets of investigations were undertaken during this study.

Study I: Long-term impact of organic and inorganic fertilizers and amendments on soil physical properties under maize-wheat cropping.

Study II: Soil physical characterization and carbon management index under different long-term cropping systems with and/or without organic amendments.

A. Study I: Long-term impact of organic and inorganic fertilizers and amendments on soil physical properties under maize-wheat cropping.

Soil physical properties were studied in an on-going long-term field experiment under maize-wheat cropping. The experiment was established in *rabi*, 1972-73 with ten treatments comprising different combinations of NPK, lime, zinc and FYM (Table 3.1). The eleventh treatment, consisting of 100 per cent NPK (-S) was introduced in *kharif*, 1981. The experiment is laid in randomized complete block design with four replications. The size of each plot is 15 m^2 (5m x 3m).

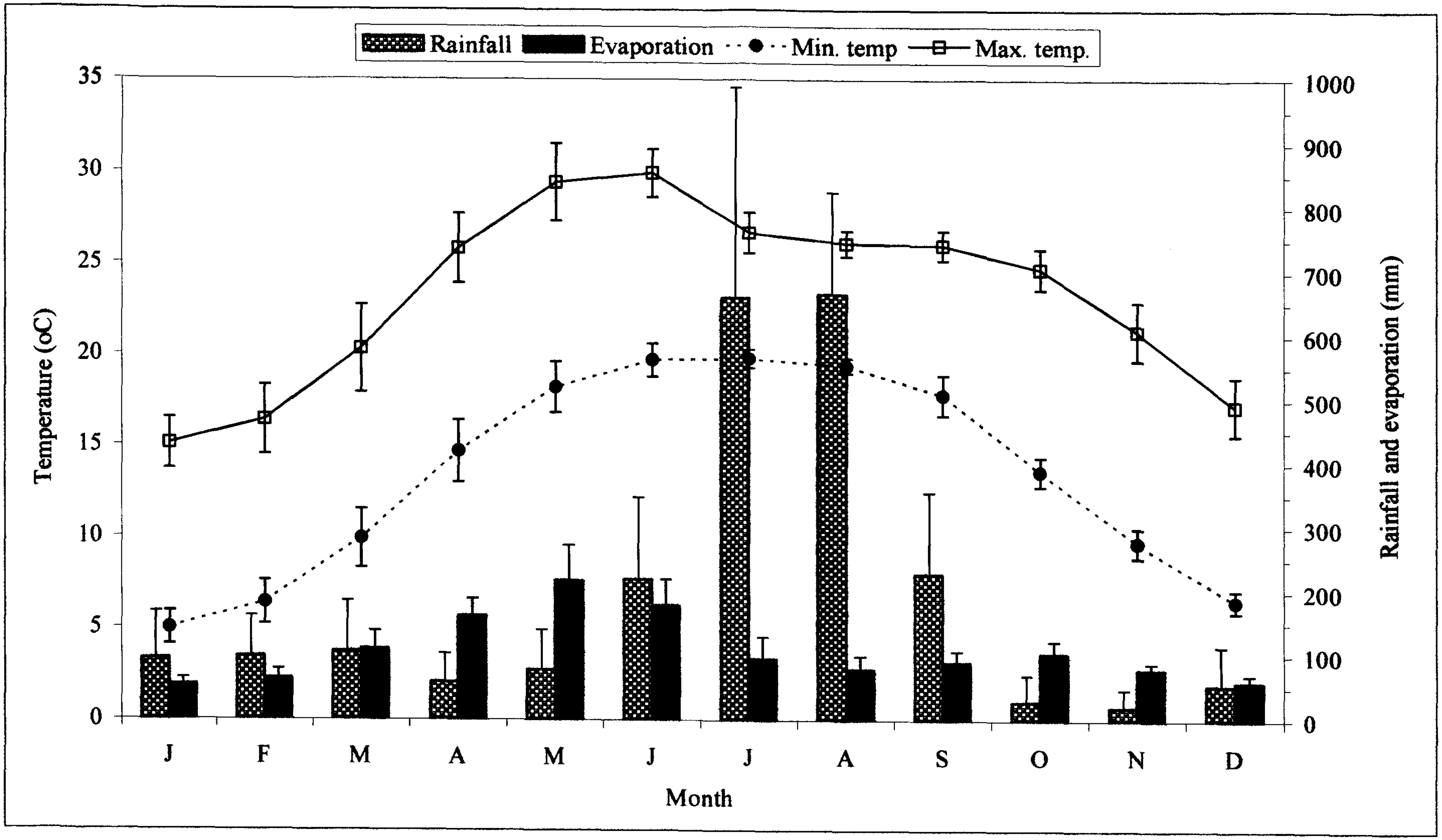


Fig. 3.1 Mean monthly rainfall and air temperature of Palampur (HP) for the period 1974-2004 (bars indicate standard deviation)

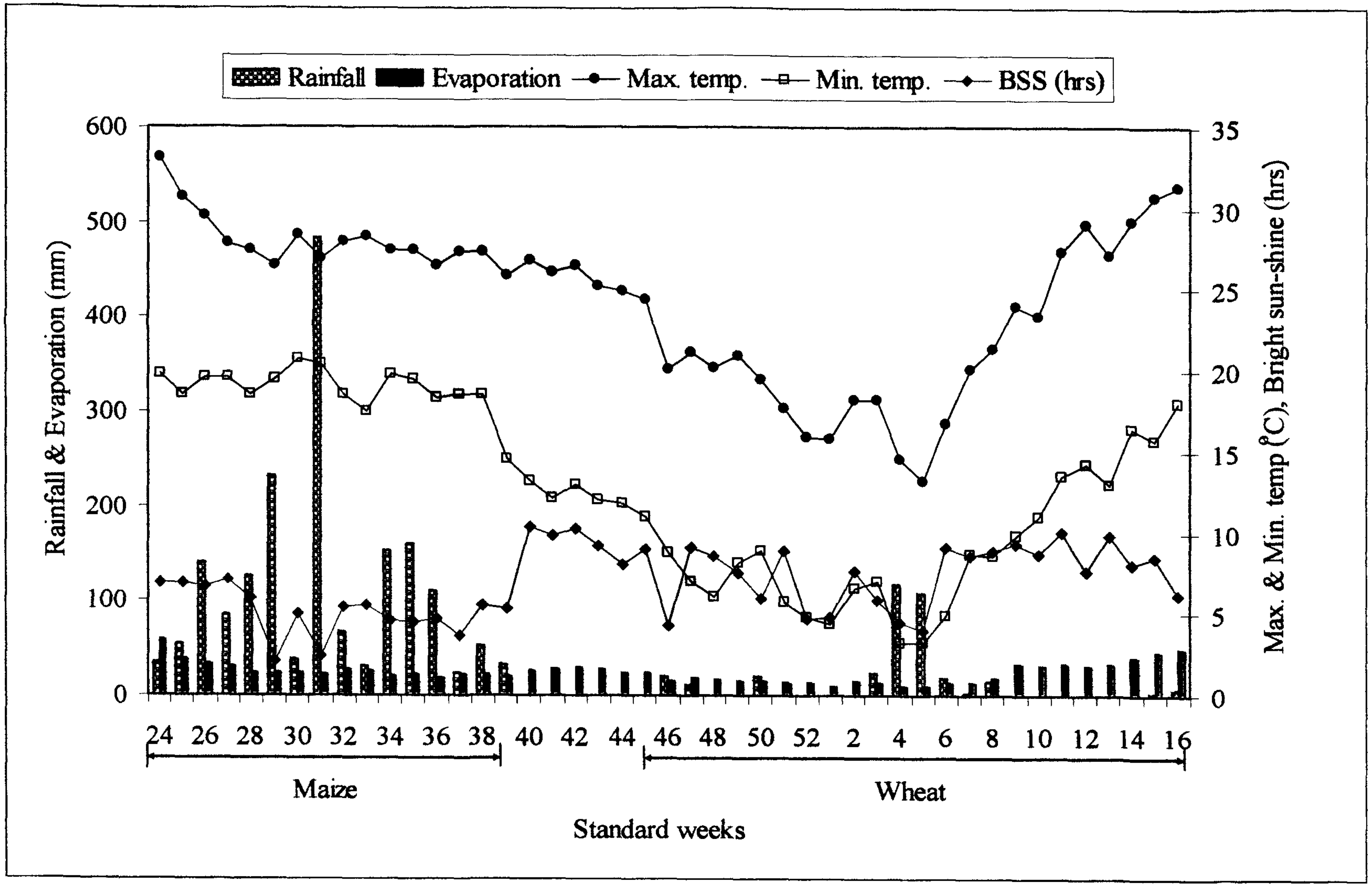


Fig. 3.2 Mean weekly meteorological data during 2003-04

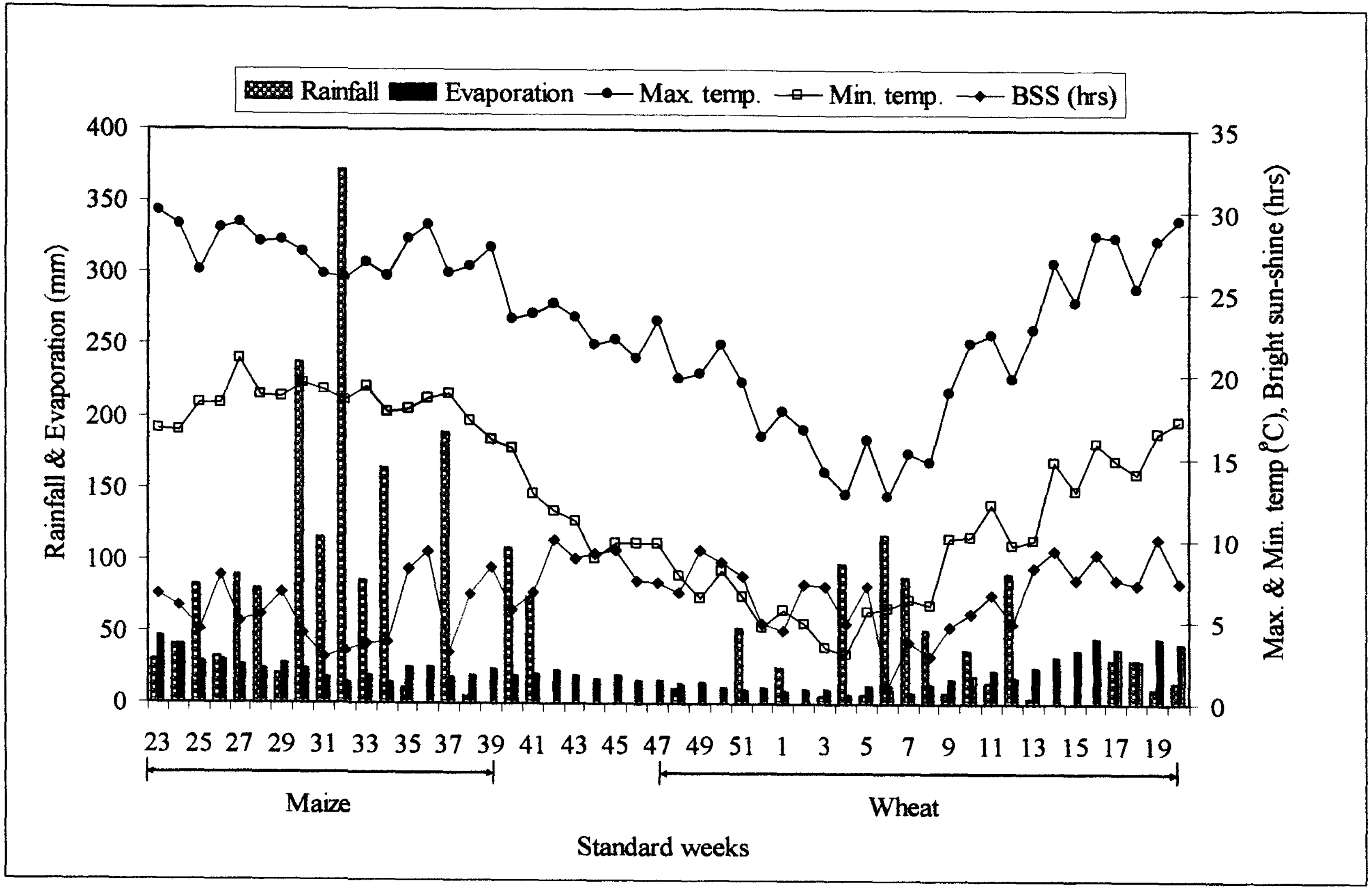


Fig. 3.3 Mean weekly meteorological data during 2004-05

Table 3.1 Treatment details of long-term field experiment on maize-wheat cropping since 1972-73.

S.No.	Treatment	S.No.	Treatment
1	Control	7	100% NPK + FYM
2	100% N	8	100% NPK + lime
3	100% NP	9	100% NPK (-S)*
4	100% NPK (Optimal dose)	10	50% NPK (Sub-optimal dose)
5	100% NPK + Hand weeding	11	150% NPK (Super-optimal dose)
6	100% NPK + Zn		

* Introduced in 1980-81

However, for the present study the following six treatments were selected:

1. Control	2. 100% N	3. 100% NP
4. 100% NPK	5. 100% NPK + FYM	6. 100% NPK + lime

Henceforth, these treatments will be referred to as control, N, NP, NPK, NPK + FYM and NPK + lime, respectively.

The NPK treatment corresponds to the state level recommendations for respective nutrients, which is 120 kg N-60 kg P_2O_5-40 kg K_2O ha^{-1} for maize and 120 kg N-60 kg P_2O_5-30 kg K_2O ha^{-1} for wheat. Half dose of N and full dose of P and K were applied at the time of sowing of both the crops. The remaining N was top dressed in 2 equal splits each at knee-high and tasseling stage of maize, and maximum tillering and flowering stage of wheat. The sources of N, P and K were urea, single superphosphate and muriate of potash, respectively. The FYM was applied at the rate of 10 t ha^{-1} on fresh weight basis to maize crop only, which is a common practice with the farmers of the region. The FYM contained on an average about 60% moisture, and 1.01, 0.26 and 0.40% of N, P and K, respectively, on dry-weight basis. Thus, 10 t FYM, on fresh-weight basis, contained about 40 kg N, 10 kg P and 16 kg K. Lime was added to maize crop in one treatment (NPK + lime) at 900 kg ha^{-1} as marketable lime ($CaCO_3$), to bring the soil pH to about 6.5. The planting and harvesting dates of wheat and maize crops are given in Table 3.2.

Table 3.2 Planting and harvesting dates of maize (*kharif*) and wheat (*rabi*) crops

Crop	Variety	Sowing date	Harvesting date
Maize (*kharif*, 2003)	KH-101	June 16, 2003	September 30, 2003
Wheat (*rabi*, 2003-04)	PBW-343	November 6, 2003	April 19, 2004
Maize (*kharif*, 2004)	KH-101	June 8, 2004	September 30, 2004
Wheat (*rabi*, 2004-05)	HS-240	November 25, 2004	May 16, 2005

Chemical weed control measures were followed in both the crops. Wheat was irrigated twice (15th January, 2004 and 12th March, 2004) during 2003-04, while only once (23rd April, 2005) during 2004-05 cropping season. Grain and straw yields were recorded separately at each crop harvest.

3.2.1 Characterization of experimental soil

Some important physical, chemical and physico-chemical characteristics of the experimental soil (0-0.15 m) determined at the initiation of the experiment (1972) are given in Table 3.3.

Table 3.3 Some initial physical, chemical and physico-chemical characteristics of the experimental soil (1972) (Sharma *et al.*, 2002)

Parameter	Value	Method used
Mechanical separates (%)		
Sand	29	International Pipette method (Piper, 1966)
Silt	47	
Clay	24	
Textural class	Silty loam	International Society of Soil Science (ISSS)
Bulk density (Mg m^{-3})	1.31	Core Method (Singh, 1980)
Organic Carbon (g kg^{-1})	7.9	Rapid titration method (Walkley and Black, 1934)
pH (1 : 2.5, soil : water)	5.8	Glass Electrode pH meter (Jackson, 1973)
Available N (kg ha^{-1})	736	Alkaline permanganate method (Subbiah and Asija, 1956)
Available P (kg ha^{-1})	12	0.5 M $NaHCO_3$ (pH 8.5) method (Olsen *et al.*, 1954)
Available K (kg ha^{-1})	194.2	Neutral normal ammonium acetate method (Merwin and Peech, 1951)
CEC [cmol (p^+) kg^{-1}]	12.1	Neutral normal ammonium acetate extraction method (Jackson, 1973)

A soil profile was exposed up to a depth of 0.90 m in an area adjoining the experimental site in November, 2003. It was treated as reference soil. Soil samples were collected at every 0.15 m depth-interval and were analyzed for pH, organic carbon, available N, P and K, cation exchange capacity using standard methods (Table 3.3), soil texture as per USDA (Piper, 1966), particle density by pycnometer method (Black, 1965), bulk density by core method (Singh, 1980), saturated hydraulic conductivity by constant water head method (Klute, 1965) and water retention of disturbed soil samples at 0, -33 and –1500 kPa potential using pressure plate apparatus (Soil Moisture Equipment Co., Santa Barbara, USA). These data (Table 3.4) were used in field water balance studies.

Table 3.4 Important physical, chemical and physico-chemical characteristics of reference soil profile

Parameter	Soil depth (m)					
	0-0.15	0.15-0.30	0.30-0.45	0.45-0.60	0.60-0.75	0.75-0.90
Mechanical separates (%)						
Sand	22	24	19	17	23	27
Silt	54	49	51	51	44	43
Clay	24	27	30	32	33	30
Particle density (Mg m^{-3})	2.58	2.59	2.59	2.60	2.60	2.60
Bulk density (Mg m^{-3})	1.32	1.38	1.33	1.27	1.30	1.35
pH (1 : 2.5, soil : water)	5.5	5.5	5.6	5.7	5.7	5.6
Organic carbon(g kg^{-1})	13.8	10.2	6.1	4.7	3.5	2.6
Available N (kg ha^{-1})	392	330	236	189	173	141
Available P (kg ha^{-1})	16.8	11.0	9.6	8.5	8.1	7.2
Available K (kg ha^{-1})	225	208	180	168	157	146
CEC [cmol (p+) kg^{-1}]	15.8	15.4	13.2	15.2	14.3	11.9
Saturated Hydraulic conductivity (x 10^{-6} m s^{-1})	5.03	3.28	3.01	4.92	4.67	3.17
Water retention at						
0 kPa	46.4	45.2	48.3	51.1	50.8	47.9
-33 kPa	33.1	34.8	34.7	33.7	34.1	34.3
-1500 kPa	20.5	21.5	20.9	19.8	20.3	20.9

3.2.2 Soil chemical and physico-chemical properties

Soil samples were collected from experimental plots (0 – 0.15 m depth) after harvest of wheat (*rabi*, 2003-2004), and from reference soil up to 0.90 m depth at every 0.15 m depth-interval. These samples were air dried and ground in a wooden pestle and mortar to pass through 2 mm sieve. These were then stored in polythene bags for subsequent analyses. Soil samples so processed were analyzed for pH, O.C., CEC and available N, P and K using standard methods of analysis (Table 3.3).

3.2.3 Soil physical properties

The soil physical properties determined during the course of present investigation and their methodology are discussed below. Soil texture, particle density, soil aggregation, bulk density, total porosity, pore size distribution, soil water retention, saturated hydraulic conductivity, soil-water contact angle and consistency limits were determined after wheat (2003-04) harvest; infiltration characteristics after maize (2003) harvest; air-filled porosity and soil penetration resistance in *rabi*, 2003-04 (wheat); water subsidence rate and *in-situ* layer wise water percolation in *kharif*, 2004 (maize).

I. Particle-size analysis

Particle-size analysis of soil samples collected from 0-0.02, 0.02-0.04, 0.04-0.06, 0.06-0.08, 0.08-0.10, 0.10-0.12, 0.12-0.15 and 0.15-0.30 m depths in experimental plots, and of samples from 0-0.90 m depth at 0.15 m depth-interval for reference soil was done by the International Pipette Method (Piper, 1966). The soil samples were collected from three locations in each plot and mixed into a composite sample. The textural class was determined using textural triangle given by United States Department of Agriculture (USDA).

II. Particle density

Particle density of the soil was determined by Pycnometer method (Black, 1965) using the following relationship:

$$\rho_s = \frac{(M_2 - M_1)}{M_4 - (M_3 - M_2) - M_1} \tag{3.1}$$

where, ρ_s is particle density (Mg m^{-3}), M_1 the mass of dry and empty pycnometer (g), M_2 the mass of 'pycnometer + oven-dried soil' (g), M_3 the mass of 'pycnometer + oven-dried soil + water' (g) and M_4 the mass of 'pycnometer + water' (g).

III. Structural properties

a. Bulk density: The bulk density determinations were made for whole soil and soil aggregates (2-8 mm diameter). The bulk density of whole soil from plots (0-0.15 and 0.15-0.30 m depths) and reference soil (upto 0-0.90 m depth at 0.15 m depth intervals) was determined using standard Core Sampler method (Singh, 1980). Metallic cores having 0.06 m length and 0.054 m internal diameter were used for collecting undisturbed soil samples of known volume. Soil samples were collected from the middle of each soil layer. The whole soil sample was oven-dried at 105 ^{0}C until constant mass and bulk density was determined as the ratio of soil mass to the volume of the core.

Bulk density of soil aggregates was determined by mercury (Hg) displacement method. A relatively small moisture box, capable of accommodating 4-5 soil aggregates (2-8 mm diameter) was filled with Hg to the brim. Mass of 'moisture box + Hg' (m_1 g) was recorded. Soil aggregates, 4-5 in number, were oven dried, weighed (m_a g) and put in the moisture box filled with Hg. The aggregates were pressed into the moisture box with a transparent plastic strip having a small hole in the centre to remove the Hg displaced by the aggregates in the moisture box. The mass of the 'moisture box + Hg + aggregates' (m_2 g) was recorded. Then the bulk density of aggregates was determined using the following relationship:

$$\rho_b(aggregates) = \frac{m_a}{[m_1 - (m_2 - m_a)]/\rho_{Hg}} \tag{3.2}$$

where, ρ_{Hg} is the density of Hg (13.6 Mg m^{-3}).

b. Total porosity: The total porosity (f) of the whole soil (0-0.15 and 0.15-0.30 m depths) and soil aggregates (2-8 mm diameter) was determined from their particle and bulk density values, using the following relationship:

$$f = \left(1 - \frac{\rho_b}{\rho_s}\right) \times 100 \tag{3.3}$$

where, f refers to the total porosity (%), ρ_b the bulk density (Mg m^{-3}) and ρ_s the particle density (Mg m^{-3}).

c. Air-filled porosity: The air-filled porosity (f_a) was determined at 0.06-0.09 and 0.15-0.18 m soil depths at frequent intervals starting after a heavy rainfall during the *rabi* season. Air-filled porosity was determined using the following equation:

$$f_a = f - \theta \tag{3.4}$$

where, f_a, f and θ refer to air-filled porosity (%), total porosity (%) and volumetric water content (%), respectively. Volumetric water content was obtained by multiplying gravimetric moisture content with the bulk density of soil layer. For determining gravimetric moisture content, soil samples were taken with the help of a tube auger.

d. Water-stable aggregates: For determining the water-stable aggregates, soil samples were collected by pushing a metal core, 0.15 m long and 0.103 m internal diameter, to 0.15 m depth. The moist soil samples were air-dried, gently broken into aggregates and passed through 8 mm and 2 mm sieves. The aggregates retained on 2 mm sieve (i.e. 2-8 mm diameter) were used for wet sieving. The wet-sieving was done with Yoder's apparatus (Yoder, 1936) for half an hour by using the procedure as mentioned by Singh (1980). The water-stable aggregates were expressed as WSA>0.25 mm diameter (%) and mean-weight diameter (MWD, mm) (Van Bavel, 1949). The WSA>0.25 mm diameter and MWD were computed as follows:

$$WSA > 0.25\,mm = \left(\frac{mass\ of\ WSA > 0.25\ mm}{total\ mass\ of\ aggregates} \right) \times 100 \qquad (3.5)$$

$$MWD\ (mm) = \sum d_i m_i \qquad (3.6)$$

where, d_i is the mean diameter of a given aggregate-size fraction (mm) and m_i the mass of that fraction in soil sample.

e. Soil penetration resistance: Soil penetration resistance (SPR) refers to the resistance offered by a soil to a metal probe (representing plant root) pushed into soil. The SPR as a function of soil moisture content was determined at 0.06 and 0.15 m soil depths at frequent intervals starting after a heavy rainfall during wheat crop. A Proctor penetrometer, having 0.18 m long probe with a flat tip of 1.61 x 10^{-4} m^2 surface area, was used for SPR determinations.

For determining SPR at 0.06 and 0.15 m soil depths, auger holes (with tube auger) were made to the required depths. The probe of the penetrometer was inserted into the hole and pushed 0.03 m into the soil. After recording the SPR value, soil sample from the same layer (0.03 m thick) was collected with the help of a tube auger for determining gravimetric moisture content, which was then converted into volumetric moisture content. The SPR versus volumetric moisture content values were plotted. The relationship was used to determine "Non-Limiting Water Range" (NLWR).

IV. Hydraulic properties

a. Soil water content: Soil water content was determined gravimetrically upto 0-0.90 m depth in 0-0.05, 0.05-0.15, 0.15-0.30, 0.30-0.45, 0.45-0.60 and 0.60-0.90 m soil layers at sowing, tillering initiation, flowering initiation, physiological maturity, one day before and after each irrigation and at crop harvest. The soil water content was calculated by the following formula:

$$w = \frac{M_s - M_d}{M_d} \times 100 \tag{3.7}$$

where, w is soil water content (%), M_s the fresh mass of soil sample (g) and M_d the oven-dried mass of soil sample (g). The mass wetness was converted into volume wetness for each soil layer by multiplying it with the bulk density of respective soil layer. These data were used to compute equivalent water depth in 0-0.90 m profile by multiplying volume wetness with the soil depth as follows:

$$D_w = \frac{\theta \times d}{100} \tag{3.8}$$

where, D_w is equivalent water depth (mm). θ the volumetric moisture content (%) and d the thickness of soil layer (mm).

b. Soil water retention: Soil water retention curve was determined after wheat harvest (2003-04). Soil core samples, 0.03 m long and 0.054 m dia were collected from each plot in the middle of 0-0.075 m soil layer with the help of metal cores. Water retention at 0, -6, -10, -33, -600 and -1500 k Pa matric potential was determined with the help of Pressure Plate Apparatus (Soil Moisture Equipment Co., Santa Barbara, California, USA).

The data for water retention in undisturbed soil samples were used to determine pore-size distribution using capillary-rise equation as follows:

$$h = \frac{2\Gamma Cos\theta}{\rho_w g r} \tag{3.9}$$

or

$$h = \frac{4\Gamma Cos\theta}{\rho_w g d} \tag{3.10}$$

where, h is the pressure applied (cm), Γ the surface tension (dynes cm^{-1}), θ the soil-water contact angle in degrees, ρ_w the density of water (g cm^{-3}), g the acceleration due to gravity (cm s^{-2}), and r and d the radius and diameter of the pores (cm).

Soil-water contact angle is so small that Cos θ is practically equal to one, and at 20 ^{0}C, the values of other parameters are:

Γ = 72.75 dynes cm^{-1}

ρ_w = 0.998 g cm^{-3}

g = 981 cm s^{-2}

Using these values, eqn. (3.10) reduces to

$$h = \frac{0.298}{d} \cong \frac{0.3}{d} \qquad (3.11)$$

Using eqn. (3.11), the values equivalent to different pore sizes were computed. The volume of each pore range was then calculated by determining the volume of water retained by the soil between the equivalent suction values. Based on these values, volumes of transmission pores (>50 μm), water storage pores (50-0.5 μm), and residual pores (<0.5 μm) were determined (Greenland, 1979).

c. Plant-available water capacity (PAWC): The PAWC was determined from the soil-moisture retention for different treatments (0-0.15 and 0.15-0.18 m depths) as follows:

$$PAWC = FC - PWP \qquad (3.12)$$

where, FC is the field capacity, i.e. moisture retained at -10 k Pa matric potential, and PWP the permanent wilting point, i.e. moisture retained at -1500 k Pa matric potential.

d. Soil infiltrability: The infiltration behaviour of the soil under different treatments was studied at the harvest of maize crop using double ring infiltrometers. The infiltrometers were pushed vertically into the ground to a depth of 0.15 m. Water was filled almost to the same level in the inner and outer infiltrometers. The volume of water infiltered into the soil as a function of time was measured by replacing the water receded inside the inner infiltrometer with the help of a measuring cylinder to a pre-fixed level (using a pointed nail). Regular determinations were made at periodic intervals until the steady-state condition of water flux was reached, and Kostiakov-Lewis constants (Hillel, 1998) were calculated. The cumulative infiltration (*I*) and infiltration rate (*i*) were calculated as follows:

$$I = kT^{a} \tag{3.13}$$

$$i = akT^{a-1} \tag{3.14}$$

where, *T* is the intake opportunity time and *a* and *k* are the empirical parameters obtained from infiltration data obtained. The water intake rates (*i*) as well as the cumulative intake (*I*) were plotted on a simple scale as a function of time.

e. Saturated hydraulic conductivity: The saturated hydraulic conductivity was determined by the constant head method of Klute (1965). Undisturbed soil cores were collected from 0-0.15 m soil depth in triplicate using metal cores of 0.11 m length and 0.081 m diameter at crop harvest. Saturated hydraulic conductivity was determined as follows:

$$K_s = \frac{Q}{AT} \times \frac{L}{(L+H)} \tag{3.15}$$

where, K_s is saturated hydraulic conductivity (m s^{-1}), Q the amount of water (m^3) passed through the soil cross-sectional area A (m^2) and length L (m) in time T (s), and H the depth of water (m) maintained at the soil surface.

f. *In-situ* layer-wise water percolation: *In-situ* layer-wise water percolation was determined in 0-0.25 m soil layer at 0.05 m depth intervals during the maize crop. An air tight assembly was designed using a core (bottomless H_2O_2 bottle) and a burette. The core was pressed into the 0.05 m layer and filled with water. A burette filled with water was then fixed over the core through a rubber cork. The amount of water percolating through the soil layer (from burette) was observed periodically, until a constant value was achieved. Then the core along with the soil was removed without disturbing the soil below, and the core was pressed into the next 0.05 m depth. The percolation rate for subsequent layers was determined as described above.

g. Water subsidence: The subsidence rate of water was determined in each maize plot during rainy season. The plots were sealed from all sides with strong dikes to prevent water leakage from the sides. The rain water was allowed to stagnate in each plot. After the rain stopped, the rate of recession of water in each plot was recorded with the help of a scale placed on a fixed platform.

h. Soil-water contact angle: Air-dry soil passed through 2 mm sieve was packed into graduated 0.70 m long and 10 mm dia glass tubes, closed at one end with a piece of muslin cloth. For uniform packing, the soil was poured into the entire length of glass tube in one lot. It was gently tapped on table over a distance of about 3-5 cm for one hundred times for the settling of soil particles. The final length of the soil was about 0.55 m. Four such soil columns per treatment were prepared in this way.

The glass tube was placed vertically in metallic stands. Two glass tubes were dipped in ethanol and the other two in distilled water contained in 100 ml beaker each. The height of capillary rise of ethanol and water in glass tubes was recorded after 24 hours. The contact angle was determined by using capillary-rise equation as follows:

$$h = \frac{2\Gamma Cos\theta}{\rho g r} \tag{3.16}$$

or

$$r = \frac{2\Gamma Cos\theta}{\rho g h} \tag{3.17}$$

where, h is the height of capillary rise (cm), Γ the surface tension of liquid (dynes cm^{-2}), θ the contact angle in degrees, ρ the density of liquid (g cm^{-3}), g the acceleration due to gravity (cm s^{-2}) and r the average radius of capillaries (cm).

The value of r was calculated from eqn. (3.17) by using data on capillary rise of ethanol, assuming soil-ethanol contact angle to be zero, so that Cos θ is equal to 1. Using the values of Γ, ρ and Cos θ for ethanol, the capillary-rise equation (3.17) would become

$$r = \frac{2 \times 22.32 \times 1}{0.789 \times 981 \times h_{(ethanol)}}$$

$$= \frac{0.05767}{h_{(ethanol)}} \qquad (3.18)$$

The value of r computed from eqn. (3.18) was used to determine the soil-water contact angle (θ), assuming pore-size distribution in soil columns used for capillary rise of water and ethanol as identical. The capillary-rise equation (3.17) for water would be

$$r = \frac{2 \times 72.75 \times Cos\theta}{0.998 \times 981 \times h_{(water)}}$$

$$\text{or} \quad h_{(water)} = \frac{2 \times 72.75 \times Cos\theta}{0.998 \times 981 \times r}$$

$$\therefore \quad Cos\theta = 6.729 \times r \times h_{(water)}$$

$$\text{hence} \quad \theta = Cos^{-1}\left\{6.729 \times r \times h_{(water)}\right\} \qquad (3.19)$$

V. Mechanical properties

a. Consistency limits: The term consistency conveys the idea of degree of cohesion between the soil particles. Consistency limits indicate the soil moisture content limits for various states of consistency. The consistency limits are: the liquid limit (the moisture content at which a soil transforms from plastic to liquid state), the plastic limit (the moisture content at which a soil transforms from plastic into semi-solid state) and shrinkage limit (the moisture content at which a soil transforms from semi-solid state to solid state).

The consistency limits of experimental soil were determined after the harvest of wheat crop (2003-04). Soil samples were collected from 0-0.15 m soil layer from each plot.

They were air dried, passed through 2 mm sieve and analyzed for different soil consistency limits as follows:

i. Liquid limit (LL): Liquid limit was determined according to ASTM (American Society of Testing Materials) procedure using Casagrande's liquid limit device. About 200 g soil sample was taken to make stiff paste with distilled water. About 30 g of this paste was put in the cup of the device so as to form a 0.01 m thick layer of paste. The cup was pre-adjusted to 0.01 m drop. With the help of a groove tool, 0.01 m groove was cut at the center of the paste. The crank was turned at two revolutions per second and number of taps required to close the groove at the bottom was recorded. The procedure was repeated several times at different moisture contents. Five observations of number of taps (varying between 18 and 32) and the corresponding gravimetric moisture content of soil were recorded. Observations with number of taps <18 or >32 were discarded. The liquid limit (per cent, mass basis) was determined as follows:

$$LL = w_n\left(\frac{N}{25}\right)^{0.12} \tag{3.20}$$

where, N is the number of taps required to close the groove in the soil paste having gravimetric moisture content w_n (per cent, mass basis).

ii. Plastic limit (PL): About 10-15 g of stiff paste of soil was kneaded to a ball and rolled between fingers to form an approximately 3 mm dia thread. The procedure was repeated until the thread began to crumble (at 3 mm dia). Corresponding moisture content of soil was determined by oven-dry method (per cent, mass basis) to give the plastic limit.

iii. Shrinkage limit (SL): Saturation paste of soil was prepared. The paste was transferred into small, greased shrinkage dishes of known volume with gentle tapping for exclusion of air bubbles, if any. The top of the shrinkage dish was cleared off excess soil by means of a straight edge. The mass of 'dish + soil' was recorded. Dish containing soil was oven dried, and the mass of 'dish + oven dried soil' was recorded. These data were used to compute the moisture content of saturation paste. The volume of dried soil cakes was determined by mercury displacement method as mentioned in para 3.2.1.2.2.1 (c). The shrinkage limit (per cent, mass basis) was calculated as follows:

$$SL = w_i - \left[\frac{(v_i - v_s)\rho_w}{w_d}\right] \times 100 \qquad (3.21)$$

where, w_i is the initial moisture content of saturation paste (per cent, mass basis), v_i initial volume of soil cake, i.e. the volume of shrinkage dish (cm^3), v_s the volume of oven-dry soil cake (cm^3), ρ_w the density of water considered as 1.0 g cm^{-3} and w_d the dry mass of soil cake (g).

iv. Plasticity index (PI): Plasticity index indicates the moisture range through which soil has the property of a plastic material. The plasticity index (per cent, mass basis) was determined as follows:

$$PI = LL - PL \qquad (3.22)$$

v. Friability range: Friability range indicates the moisture range at which soil has maximum friability. The friability range (per cent, mass basis) was determined as:

$$Friability\ Range = PL - SL \qquad (3.23)$$

3.2.4 Field water balance

a) Determination of crop water use: Soil moisture content was determined upto 0-0.90 m depth in 0-0.05, 0.05-0.15, 0.15-0.30, 0.30-0.45, 0.45-0.60 and 0.60-0.90 m soil layers at different growth stages of wheat, viz. sowing, initiation of tillering, flowering initiation, dough stage and crop harvest, using the procedure described earlier (para 3.2.3.IVa). These data were used to determine profile water use from different depths during different phenological phases viz. sowing to tillering initiation, tillering initiation to flowering initiation, flowering initiation to physiological maturity and physiological maturity to crop harvest, and for the whole cropping season i.e. from sowing to harvest. Total water use (profile water use + rainfall + irrigation) was also determined for above mentioned phenological stages.

b) Estimation of crop water use using DSSAT model: The performance of the soil water balance module (SWBM) in the models of Decision Support System for Agrotechnology Transfer (DSSAT) version 3.5 was evaluated against soil moisture data measured during wheat crop (2003-04 and 2004-05). The SWBM in the crop growth models of DSSAT v 3.5 computes one dimensional soil water balance based on simple water accounting in each layer considered in the soil profile in a daily time step, as described by Ritchie (1998). Soil characteristics, climate parameters and crop management practices are standard inputs to the model (IBSNAT, 1990). Apart from the soil moisture content in 0-0.90 m depth at 0.15 m depth intervals at different growth stages, the following data set were generated for the validation of model:

i. Soil parameters: It included pH, organic carbon and CEC (para 3.2.2), particle-size distribution (para 3.2.3.I), bulk density (para 3.2.3.IIIa) and saturated hydraulic conductivity (para 3.2.3.IVe). The data from experimental plots under different treatments and data collected from the reference profile were used.

ii. Crop management data: Data pertaining to sowing, manure and fertilizer application, and irrigation were recorded.

iii. Plant observations: Data were recorded on days to seedling emergence, tillering initiation and 50 per cent tillering, flowering initiation and 50 per cent flowering and physiological maturity of wheat.

iv. Climatic parameters: Data on rainfall, minimum and maximum temperature, and solar radiation were recorded.

The genetic coefficients of wheat (HS-240) used in the simulation model are given in Appendix-IV.

3.2.5 Crop yields

Grain and stover yields of maize were recorded at harvest (*kharif*, 2003 and 2004). Grain yield of maize was reported at twelve percent moisture content and stover yield on oven-dry basis. Grain and straw yields of wheat (2003-04 and 2004-05) were recorded at crop harvest and reported on air-dry basis. The grain yields of both maize and wheat during a cropping cycle were added to compute the system productivity.

B. Study II: Soil physical characterization and carbon management index under different long-term cropping systems with and/or without organic amendments

Some treatments with and/or without organics in different on-going long-term field experiments under different cropping systems at the university farm were selected (Table 3.5) for the determination of non-limiting water range (NLWR) and carbon management index (CMI) (described below in para 3.2.6 and 3.2.7, respectively). The soil texture was silty loam (ISSS) in long-term fertilizer experiment under maize-wheat cropping for 32 years and silty clay loam in all other field experiments.

3.2.6 Non-limiting water range

Physical productivity of soil under different treatments was characterized using Non-limiting water range (NLWR), a single value index given by Letey (1985). Higher the NLWR, better is the soil physical productivity and vice-versa.

The NLWR was computed as the difference between the soil moisture content at which the air-filled porosity (f_a) was 10% (upper limit of moisture content) and the moisture content at which the soil penetration resistance (SPR) was 2 MPa (lower limit of moisture content) at 0.15 m soil depth. The value of 2 MPa SPR was used based on previous studies (Sharma and Bhushan, 2001). At this SPR, the root mass density of wheat

Table 3.5 Treatment details of different cropping systems selected for determination of non-limiting water range (NLWR) and carbon management index (CMI)

Cropping system	Duration (years)	Treatments
Maize-Wheat	32	Control 100% N 100% NP 100% NPK 100% NPK + FYM 100% NPK + lime
Maize-Wheat	13	100% NPK
Soyabean-Wheat	18	100% NPK
Rice-Wheat	18	100% NK 100% NK + Lantana
Rice-Wheat	14	Control 100% NPK 50% NPK + FYM 50% NPK + WS
Rice-Wheat	6	100% NPK 75% N 100% PK + 25%N (Lantana)
Rice-Wheat	6	100% NPK 100% NPK + Lantana[§]
Guinea grass	7	100% NPK
Setaria grass	6	100% NPK

[§] No-tillage in *rabi* season

was reduced to about half. The f_a and SPR were determined frequently at regular intervals, starting immediately after rainfall, by using the procedure as described in para 3.2.3.IIIc and 3.2.3.IIIe, respectively.

The NLWR computed for the 0.15-0.18 m soil layer was correlated with grain yields of wheat. The NLWR:PAWC ratio for the same layer was also computed. The PAWC for the 0.15-0.18 m soil layer was determined as follows

$$PAWC = FC - PWP \qquad (3.24)$$

where, FC is the field capacity, i.e. moisture retained at -10 k Pa matric potential, and PWP the permanent wilting point, i.e. moisture retained at -1500 k Pa matric potential.

3.2.7 Carbon management index

Carbon management index (CMI) was determined for treatments under different cropping systems as mentioned in Table 3.5. The soil samples collected from uncultivated and un-cleared area near each experimental site were treated as reference for various calculations. Total (C_T) and labile carbon (C_L) were determined in surface (0-0.15 m) soil samples as follows:

a. Total carbon (C_T): Total carbon in soil sample was determined by using dry combustion method of Houba *et al.* (1995), a modification of method given by Ball (1964) for the estimation of organic matter content. A 10 g sample was subjected to dry combustion in a muffle furnace at 550^0C for 3 hours. The weight loss was treated as the loss of organic matter from the soil and this was converted to carbon using the factor 1.724 (assuming that organic matter contains 58 % carbon).

b. Labile carbon (C_L): Labile carbon was estimated by the method given by Blair *et al.* (1995). The soil samples (containing 15 mg C_T) were weighed into 50 ml centrifuge tubes and 25 ml of 33 mM $KMnO_4$ was added to each vial. Blank samples, containing no soil, and samples of reference soil were analyzed in each run. The centrifuge tubes were shaken on an end-to-end shaker (with tube lying on its side) for 6 hours and then centrifuged for 5 minutes at 2000 rpm (RCF 815 g). The absorbance for the supernatant and standards were read on a spectrophotometer at 565 nm. The change in the concentration of $KMnO_4$ was used to estimate the amount of carbon oxidized, assuming that 1 mM $KMnO_4$ is consumed in the oxidation of 0.75 mM or 9 g of carbon. The results were expressed as mg C g^{-1} soil.

The CMI was determined from the values of total carbon (C_T) and labile carbon (C_L) for 0-0.15 m depth using the following formulae (Blair *et al.*, 1995)

$$CMI = CPI \times LI \times 100 \tag{3.25}$$

$$CPI = \frac{C_{T\,sample}}{C_{T\,reference}} \tag{3.26}$$

$$LI = \frac{L_{C\,sample}}{L_{C\,reference}} \tag{3.27}$$

$$L_C = \frac{C_L}{C_{NL}} \tag{3.28}$$

$$C_{NL} = C_T - C_L \tag{3.29}$$

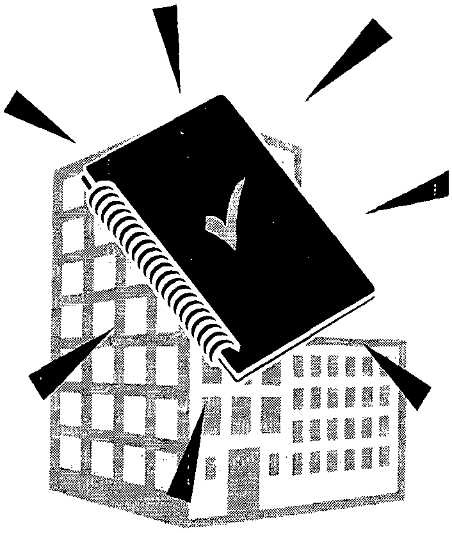
where, CPI is the carbon pool index, LI the lability index, $L_{C\ sample}$ and $L_{C\ reference}$ the lability of carbon in the experimental plot and the reference soil, respectively, and C_{NL} the non-labile carbon.

3.3 Meteorological parameters

Data on rainfall, minimum and maximum temperature, PAN-Evaporation and solar radiation for the cropping season were recorded from the Meteorological Observatory of the Department of Agronomy, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur located within 1 km distance from the experimental site.

3.4 Statistical analysis

The data generated during the course of the present investigation were subjected to analysis of variance (ANOVA) to determine the effects of treatments on various soil properties and crop yields using the IRRISTAT data analysis package. A probability level of ≤ 0.05 was considered significant.



RESULTS

Chapter IV

Results

The results emanating from the current investigation entitled "Physical characterization of an acid Alfisol under maize-wheat cropping as influenced by long-term use of chemical fertilizers and soil amendments" are presented in this chapter under the following heads:

- 4.1 Long-term effects of chemical fertilizers and amendments on soil properties
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4.1 Long-term effects of chemical fertilizers and amendments on soil properties

4.1.1 Chemical and physico-chemical properties

The important chemical and physico-chemical properties of soil (soil reaction, organic carbon, available N, P and K, and cation exchange capacity) at 0-0.15 m depth studied at wheat harvest (*rabi*, 2003-04) have been presented in Table 4.1.

4.1.1.1 Soil pH

The soil pH varied from a minimum of 4.4 in N to a maximum of 6.5 in NPK + lime treatment, and both these treatments differed significantly from rest of the treatments (Table 4.1). Soil pH in control remained practically the same (5.6) as the value (5.8) at the start of experiment (1972). Soil pH was at par in NP, NPK and NPK + FYM with values of 5.1, 5.2 and 5.1, respectively. Application of lime along with NPK increased soil pH by 1.3 units over the pH in NPK (5.2).

Table 4.1 Effect of chemical fertilizers and amendments on some soil chemical and physico-chemical properties of 0-0.15 m soil layer

Treatment	pH	SOC g kg^{-1}	Available nutrients (kg ha^{-1})			CEC c mol (p^{+}) kg^{-1}
			N	P	K	
Control	5.6	7.0	243.0	5.5	122.4	11.48
N	4.4	7.2	274.4	7.0	145.1	10.84
NP	5.1	8.0	282.2	95.2	128.8	13.14
NPK	5.2	8.0	301.8	117.0	193.6	14.72
NPK + FYM	5.1	12.4	335.2	135.9	223.1	16.06
NPK + lime	6.5	8.4	299.9	121.7	200.6	15.22
LSD (P=0.05)	0.1	0.1	17.4	8.6	2.0	0.58
Initial*	5.8	7.9	736.0	12.0	194.2	12.1

* Values determined in 1972

4.1.1.2 Organic carbon

The soil organic carbon (SOC) content varied from 7.0 g kg^{-1} in control to 12.4 g kg^{-1} in NPK + FYM plots (Table 4.1). The SOC in N plots (7.2 g kg^{-1}) was very close to that in control plots. Compared to the initial (1972) SOC value of 7.9 g kg^{-1}, control and N treatments caused a significant decline in SOC, NP and NPK maintained it, while NPK + lime and NPK + FYM increased SOC values by about 6 and 57%, respectively.

4.1.1.3 Available nitrogen

The available N content varied from 243.0 kg ha^{-1} in control to 335.2 kg ha^{-1} in NPK + FYM (Table 4.1). The N and NP plots were statistically at par for available N with values of 274.4 and 282.2 kg N ha^{-1}, respectively. The NPK and NPK + lime were also statistically at par for available N, and had values higher than N and NP, but lower than NPK + FYM. Maize-wheat cropping continuously for 32 years reduced available N by half to one-third of the initial value (736 kg ha^{-1}) irrespective of any treatment.

4.1.1.4 Available phosphorus

The available P content varied from 5.5 kg ha^{-1} in control to 135.9 kg ha^{-1} in NPK + FYM (Table 4.1). Available P in N plots was statistically the same as in control. The NPK + lime and NPK were statistically at par for available P but significantly higher than NP and lower than NPK + FYM. Maize-wheat cropping for 32 years with different treatments showed differential effect on available P. While available P content decreased in control and N treatments, it increased in all other treatments over the initial value of 12.0 kg ha^{-1}. Control and N showed a decline in available P by about 54 and 42% over the initial value, while NP, NPK, NPK + lime and NPK + FYM showed an increase by 83.2, 105.0, 109.7 and 123.9 kg ha^{-1}, respectively.

4.1.1.5 Available potassium

The available K varied between 122.4 kg ha^{-1} in control to 223.1 kg ha^{-1} in NPK + FYM (Table 4.1). Available K declined in all treatments without K application over the initial value of 194.2 kg ha^{-1}; the decline was about 37, 25 and 34% in control, N and NP treatments, respectively. The NPK maintained (193.6 kg ha^{-1}) the initial K content, while NPK + lime and NPK + FYM resulted in an increase in available K by about 3 and 15%, respectively, over the initial value.

4.1.1.6 Cation exchange capacity

The long-term use of chemical fertilizers and amendments significantly affected the cation exchange capacity (CEC) of soil (Table 4.1). The CEC varied from 10.84 c mol (p^{+}) kg^{-1} in N to 16.06 c mol (p^{+}) kg^{-1} in NPK + FYM. The N plots showed a decline in CEC by about 6% over control (11.48 c mol (p^{+}) kg^{-1}). The CEC increased significantly with the use of NP, NPK, NPK + lime and NPK + FYM over control by about 14, 28, 33 and 40%, respectively. Compared to initial value of 12.1 c mol (p^{+}) kg^{-1}, CEC showed a decrease in control and N, while increase in NP, NPK, NPK + lime and NPK + FYM.

4.1.2 Physical properties

4.1.2.1 Soil texture

The mechanical separates of soil viz. sand, silt and clay (USDA), determined for 0-0.02, 0.02-0.04, 0.04-0.06, 0.06-0.08, 0.08-0.10, 0.10-0.12, 0.12-0.15 and 0.15-0.30 m soil layers, are presented in Figure 4.1 (Appendix-V). All the three separates were

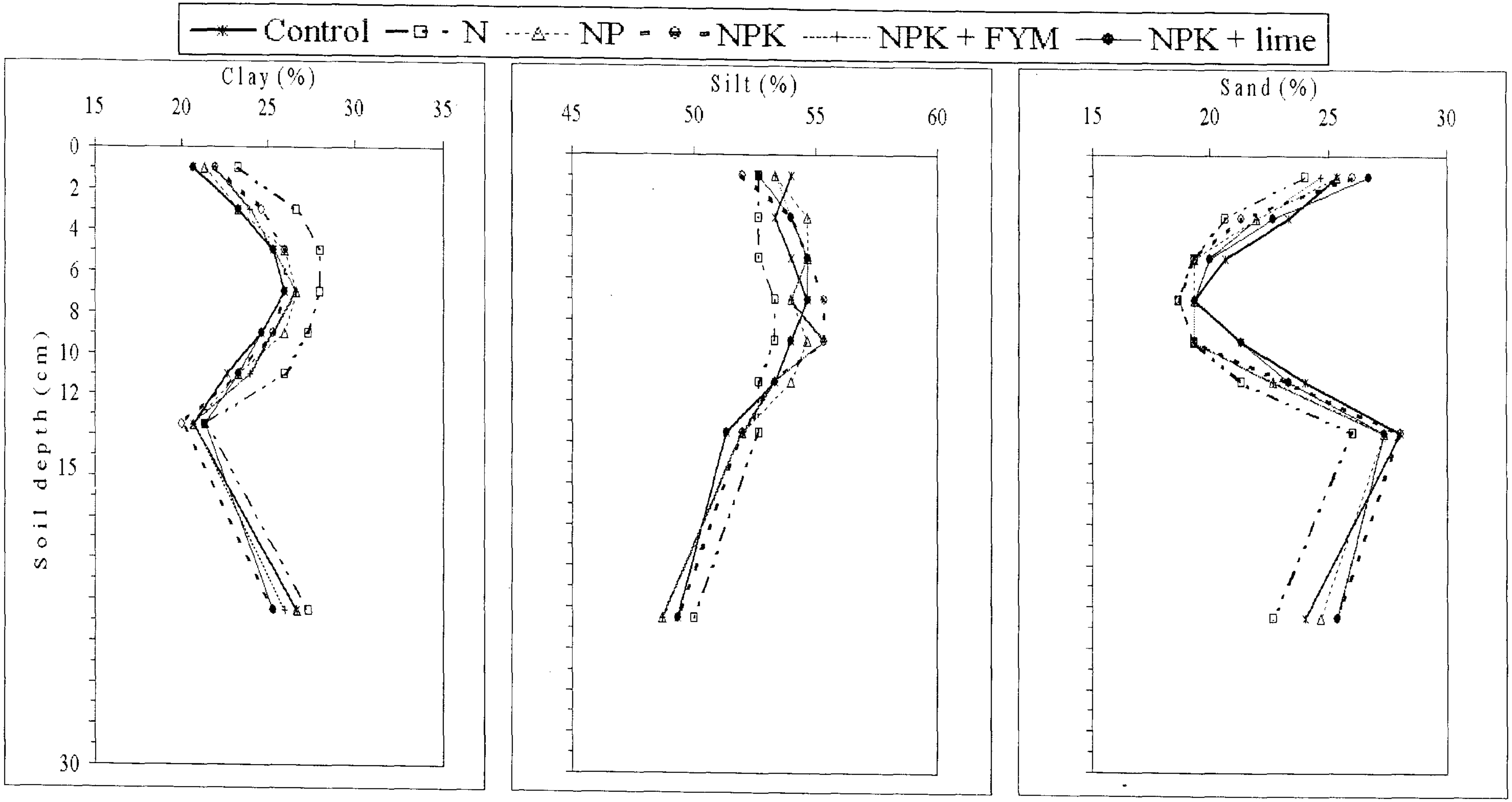


Figure 4.1 Effect of chemical fertilizers and amendments on soil mechanical separates

statistically the same under all the treatments, except N. Long-term use of N alone increased the clay content at the cost of coarser fractions. The clay content at different depths varied between 21.3 and 28.0% in N as compared to 20.7 and 26.3%, the average clay content in other treatments. Correspondingly, the sand content varied between 18.7 and 26.0% in N as compared to 19.2 and 27.6%, the average sand content in other treatments. The silt content at different soil depths, averaged over all the treatments, varied between 49.2 and 54.4%. According to these data, clay content at different depths upto 0.30 m increased by 0.7-2.9% in N treatment as compared to other treatments.

The clay content under all treatments showed a progressive increase with depth upto 0.06-0.08 m; it then decreased to 0.15 m depth and then again increased upto 0.30 m (Fig. 4.1). The sand content showed a trend just opposite to that of clay. Silt content on an average remained the same upto 0.08 m depth, and then showed a progressive decline.

The N treatment had statistically the highest clay and lowest sand content in 0-0.15 m soil layer; silt content was the same under all treatments (Table 4.2). In 0.15-0.30 m soil layer, all the three soil fractions were statistically the same in all the treatments. The clay and sand contents under all the treatments were higher while silt content lower in 0.15-0.30 m than in 0-0.15 m soil layer.

Table 4.2 Effect of chemical fertilizers and amendments on soil mechanical separates in 0-0.15 and 0.15-0.30 m soil layers

Treatment	Sand		Silt		Clay	
	0-0.15 m	0.15-0.30 m	0-0.15 m	0.15-0.30 m	0-0.15 m	0.15-0.30 m
Control	23.5	24.0	53.4	49.3	23.2	26.7
N	21.6	22.7	52.8	50.0	25.5	27.3
NP	22.5	24.7	53.8	48.7	23.7	26.7
NPK	22.7	25.3	53.7	49.3	23.6	25.3
NPK + FYM	22.5	25.3	53.7	48.7	23.8	26.0
NPK + lime	23.2	25.3	53.4	49.3	23.4	25.3
LSD (P=0.05)	1.0	NS	NS	NS	0.6	NS

The textural class (USDA) in all the treatments, except N, was silt loam in all soil samples collected at 0.02 m depth interval upto 0.15 m depth, and loam in 0.15-0.30 m soil layer. However, in N-treated plots the textural class was silt loam in 0-0.04 m, silty clay loam in 0.04-0.10 m, silt loam in 0.10-0.15 m and clay loam in 0.15-0.30 m soil depths.

4.1.2.2 Particle density

Continuous use of chemical fertilizers and amendments did not show any effect on particle density of soil. The particle density values for control, N, NP, NPK, NPK + FYM and NPK + lime treatments were 2.57, 2.57, 2.56, 2.56, 2.55 and 2.56 Mg m^{-3} in the 0-0.15 m soil depth, and 2.58, 2.58, 2.57, 2.57, 2.56 and 2.57 Mg m^{-3} in the 0.15-0.30 m soil layer, respectively, with mean values of 2.56 and 2.57 Mg m^{-3} in respective soil layers. The treatment effects were statistically non-significant.

4.1.2.3 Structural properties

a. Soil aggregation

Soil aggregation, expressed as mean weight diameter (MWD), water stable aggregates > 0.25 mm diameter (WSA) and aggregate size distribution, was significantly affected by different treatments.

The MWD ranged between 0.97 mm (N) and 3.59 mm (NPK + lime) and the differences were statistically significant (Table 4.3). The MWD decreased by about 29% under N, while increased by about 17 and 23% under NP and NPK, respectively, over the control (1.36 mm). Application of FYM and lime along with NPK showed a further increase in MWD; the respective values were higher by about 85 and 164% than in control.

Table 4.3 Effect of chemical fertilizers and amendments on mean weight diameter (MWD) and water stable aggregates (WSA)

Treatment	MWD (mm)	WSA > 0.25 mm dia (%)
Control	1.36	71.0
N	0.97	62.9
NP	1.59	77.5
NPK	1.67	78.6
NPK + FYM	2.52	83.6
NPK + lime	3.59	89.6
LSD (P=0.05)	0.22	3.7

The WSA (>0.25 mm dia) varied from 65.9% in N to 89.6% in NPK + lime treatments (Table 4.3). All the treatments, except N, had statistically higher WSA than the control. While WSA showed a decline under N by about 12% over the control, it increased under NP, NPK, NPK + FYM and NPK + lime by about 9, 11, 18 and 26%, respectively.

The size-distribution of water stable aggregates under different treatments is shown in Fig 4.2 (Appendix-VI). The WSA of any given size were lowest under N and highest under NPK + lime; values with NPK + FYM were the second highest; the control, NP and NPK showed intermediate values. According to these data, N alone caused a significant reduction in all aggregate-size fractions < 4.0 mm diameter over the control; all other treatments observed improvement in all size-fractions of WSA.

b. Bulk density

Bulk density of soil varied between 1.15 and 1.35 Mg m^{-3} in 0-0.15 m soil layer, and between 1.22 and 1.35 Mg m^{-3} in the 0.15-0.30 m soil layer; the highest and lowest values of bulk density in both soil layers were in N and NPK + FYM plots, respectively (Table 4.4).

In 0-0.15 m soil layer, the bulk density in control, N and NPK + lime plots was statistically at par and significantly the highest among different treatments. The bulk density decreased by 8.2, 9.0 and 14.2% over control with the use of NP, NPK and NPK + FYM, respectively. In 0.15-0.30 m soil layer the NP, NPK and NPK + FYM recorded the lowest, NPK + lime the intermediate, and control and N the highest bulk density values and the differences were statistically significant. The bulk density decreased by 4.4, 6.7, 7.4 and 9.6% over the control with NPK + lime, NP, NPK and NPK + FYM, respectively.

Bulk density of the aggregates (2-8 mm dia) was also significantly affected by different treatments (Table 4.4). It ranged from 1.24 Mg m^{-3} in NPK + FYM to 1.79 Mg m^{-3} in N. The bulk density of aggregates under NP, NPK and NPK + FYM was significantly

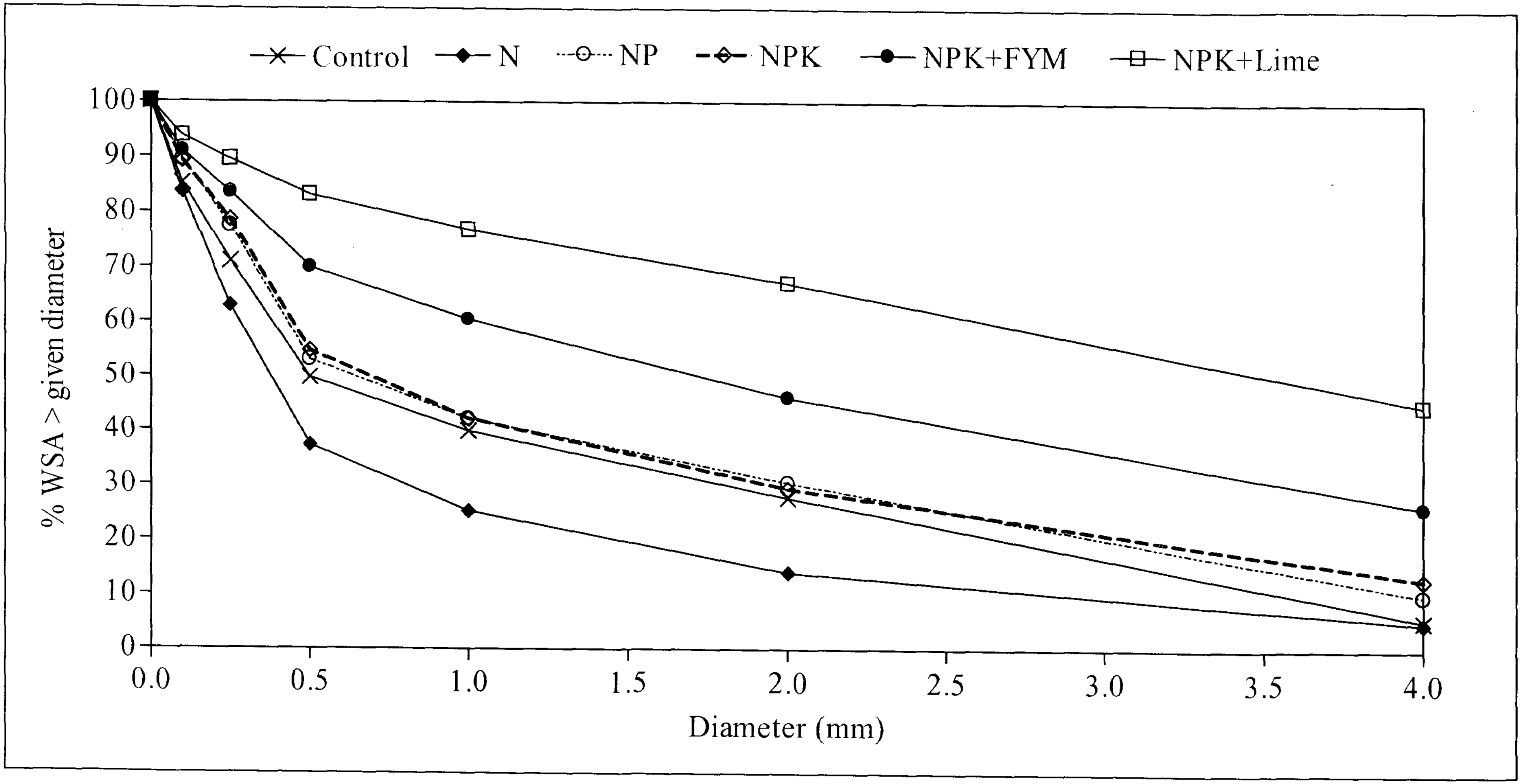


Figure 4.2 Effect of chemical fertilizers and amendments on size-distribution of water stable aggregates

lower than control (1.58 Mg m^{-3}) by about 6, 8 and 22%, respectively. The NPK + lime was statistically at par with control for bulk density of aggregates (1.55 Mg m^{-3}), but had a significantly higher bulk density than NP, NPK and NPK + FYM treatments.

Table 4.4 Effect of chemical fertilizers and amendments on soil bulk density under maize-wheat cropping

Treatment	Bulk density (Mg m^{-3})		
	Whole soil		Aggregates (2-8 mm diameter)
	0-0.15 m	0.15-0.30 m	
Control	1.34	1.35	1.58
N	1.35	1.34	1.69
NP	1.23	1.26	1.49
NPK	1.22	1.25	1.46
NPK + FYM	1.15	1.22	1.24
NPK + lime	1.32	1.29	1.55
LSD (P=0.05)	0.04	0.04	0.05

c. Total porosity

The values of total porosity of whole soil (0-0.15 and 0.15-0.30 m) and soil aggregates (2-8 mm dia) are presented in Table 4.5. In 0-0.15 m soil layer, the N treated plots had the minimum porosity (47.5%), which was statistically at par with control (47.8%) and NPK + lime (48.3%). The NP, NPK and NPK + FYM increased total porosity to 52.0, 52.5 and 54.9 %, respectively.

The 0.15-0.30 m soil layer showed relatively low values of porosity, but the trend was similar to that in 0-0.15 m layer, except in NPK + lime, which had a significantly higher porosity than control and N. The total porosity in control (47.9%) and N (48.1%) was statistically at par. Application of NPK + lime, NP, NPK and NPK + FYM increased total porosity to 49.9, 51.2, 51.3 and 52.2%, respectively.

Porosity of soil aggregates (2-8 mm dia) in the 0-0.15 m soil layer varied from 30.3% in N to 51.7% in NPK + FYM. Compared to control, aggregate porosity was significantly lower with N, at par with NPK + lime, and higher with NP, NPK and NPK + FYM.

Table 4.5 Effect of chemical fertilizers and amendments on total porosity of soil and soil aggregates under maize-wheat cropping

Treatment	Total porosity (%)		
	Whole soil		Aggregates (2-8 mm diameter)
	0-0.15 m	0.15-0.30 m	
Control	47.8	47.9	38.5
N	47.5	48.1	34.2
NP	52.0	51.2	42.0
NPK	52.5	51.3	43.2
NPK + FYM	54.9	52.2	51.7
NPK + lime	48.3	49.9	39.6
LSD (P=0.05)	1.5	0.8	2.1

d. Air-filled porosity

Air-filled porosity of 0.06-0.09 and 0.15-0.18 m soil layers as a function of soil moisture content determined during wheat season is shown in Fig. 4.3 (Appendix-VII). Air-filled porosity in both the layers at any given moisture content was lowest in N, control and NPK + lime, followed by NP and NPK, and highest in NPK + FYM. The moisture content in the 0.06-0.09 m soil layer corresponding to 10% air-filled porosity was 38.3-39.2% in N, control and NPK + lime, 42.7-43.1% in NP and NPK, and 45.7% in NPK + FYM treated plots. The corresponding moisture contents in 0.15-0.18 m soil layer were 35.4-35.9% in N, control and NPK + lime, 37.1-37.5% in NP and NPK, and 39.2% in NPK + FYM treated plots.

Air-filled porosity in 0.06-0.09 and 0.15-0.18 m soil layers as a function of time after saturation is shown in Fig. 4.4 (Appendix-VII). In the 0.06-0.09 m soil layer the 10% air-filled porosity was attained in 5 days in N, control and NPK + lime, and within a few hours after saturation in NP, NPK and NPK + FYM. In 0.15-0.18 m soil layer, the 10% air-filled porosity was reached in 16, 13, 12, 9, 9 and 5 days after saturation in plots treated with N, control, NPK + lime, NP, NPK and NPK + FYM, respectively.

e. Pore-size distribution

The pore-size distribution determined in 0-0.075 m soil layer at wheat harvest

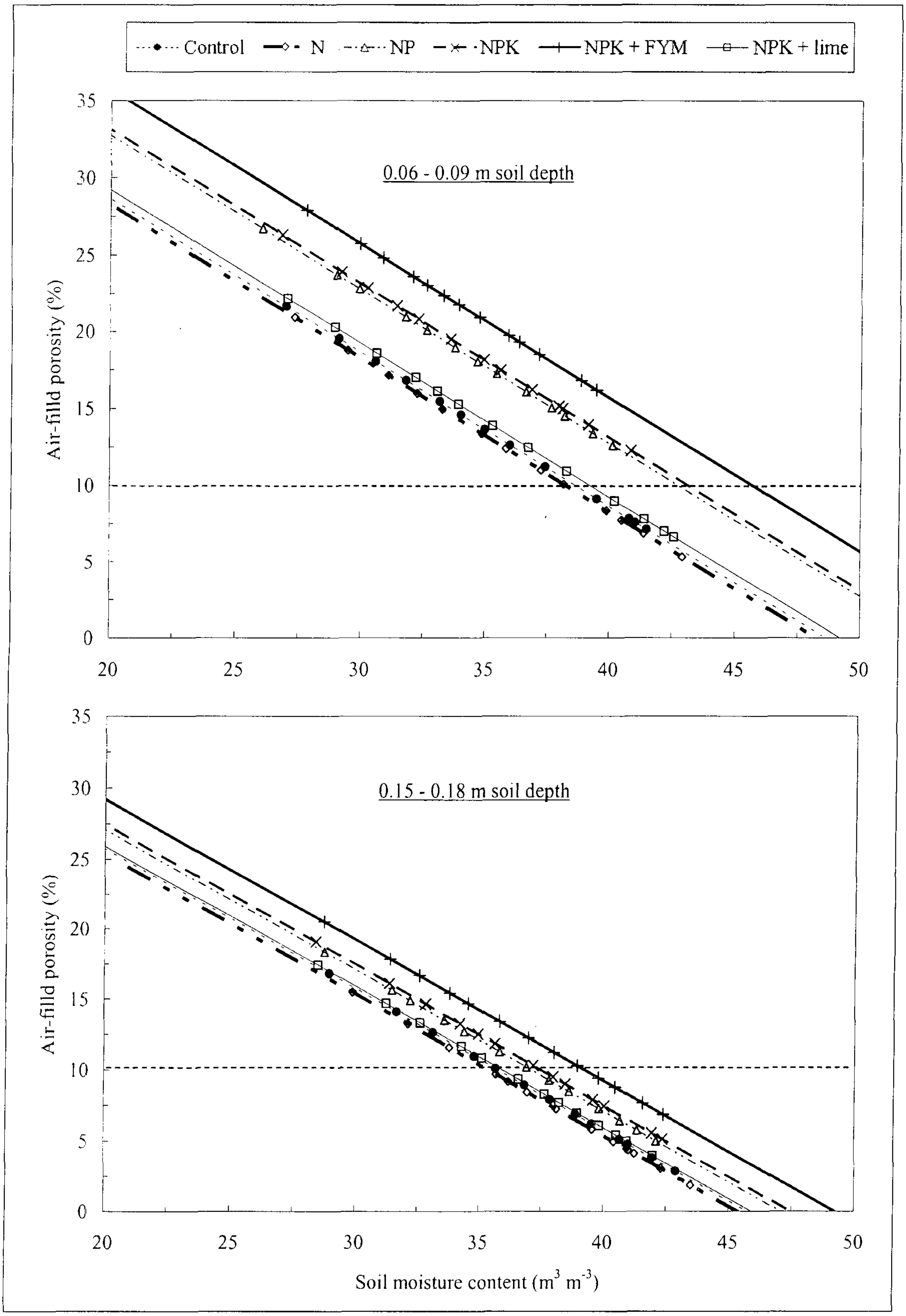


Figure 4.3 Effect of chemical fertilizers and amendments on air-filled porosity in relation to soil moisture content during wheat season

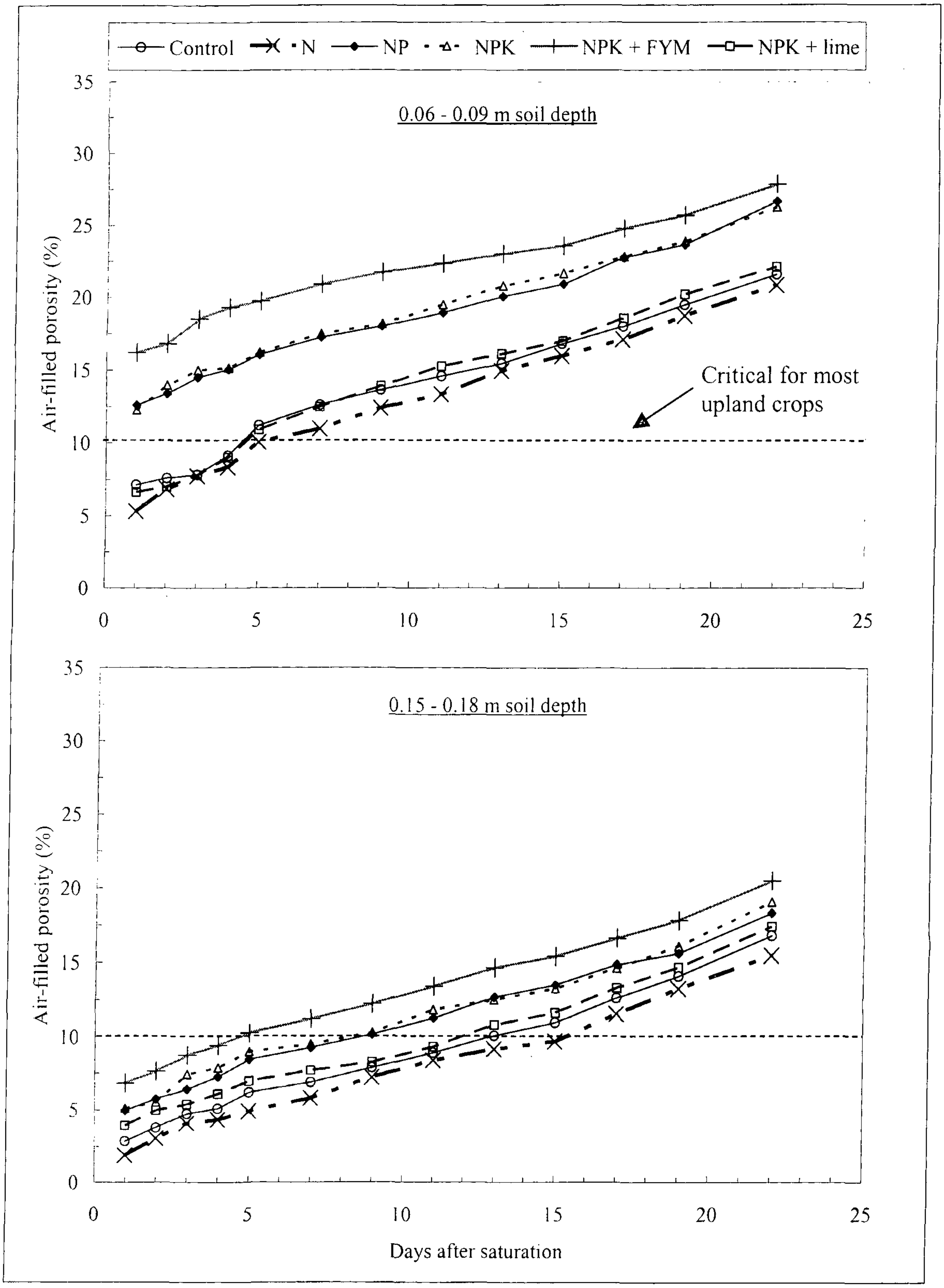


Figure 4.4 Effect of chemical fertilizers and amendments on air-filled porosity of soil as function of time during wheat season

(*rabi*, 2003-04) is presented in Fig 4.5 (Appendix-VIII). Pores of all sizes were distinctly higher in NPK + FYM, NPK and NP than in N, control and NPK + lime.

Pores were classified according to the classification given by Greenland (1979). The volumes of water transmission (>50 μm), water storage (0.5-50 μm) and residual (<0.5 μm) pores under different treatments are shown in Fig. 4.6 (Appendix-IX). The water transmission pores ranged between 18.8 and 28.2%. Compared to control (20.2%), the water transmission pores were at par in N (18.8%) and NPK + lime (21.0%), and higher in NP (26.9%), NPK (27.1%) and NPK + FYM (28.2%). The NP and NPK treatments were also statistically at par to each other. Water storage pores ranged between 32.8 and 34.7%. All the treatments were at par with each other. Residual pores decreased in all the treatments, except N (47.0%), with respect to control (46.4%). The NPK + lime had 44.3% residual pores, followed by NP (40.4%), NPK (40.2%) and NPK + FYM (37.3%).

f. Soil penetration resistance

Soil penetration resistance (SPR) values determined at 0.06 and 0.15 m soil depths at frequent intervals after heavy rainfall during wheat cropping season are shown in Fig. 4.7 (Appendix-X). The SPR was significantly affected by different treatments. Similar trend was observed at 0.06 and 0.15 m soil depths. The N treatment had the highest, while NPK + FYM had the lowest SPR at any given moisture content. The SPR in general followed the order: N > control > NPK + lime > NP > NPK > NPK + FYM.

The SPR at both soil depths was linearly, negatively and significantly correlated with soil moisture content (θ, per cent) as follows:

At 0.06 m soil depth: (n = 52, $25.0 \leq \theta \leq 44.5$)

$$\text{SPR (Control)} = 3.406 - 0.070\,\theta; \quad R^2 = 0.772^{**} \tag{4.1}$$

$$\text{SPR (N)} = 3.546 - 0.072\,\theta; \quad R^2 = 0.821^{**} \tag{4.2}$$

$$\text{SPR (NP)} = 3.230 - 0.067\,\theta; \quad R^2 = 0.744^{**} \tag{4.3}$$

$$\text{SPR (NPK)} = 3.187 - 0.067\,\theta; \quad R^2 = 0.718^{**} \tag{4.4}$$

$$\text{SPR (NPK + FYM)} = 3.100 - 0.066\,\theta; \quad R^2 = 0.678^{**} \tag{4.5}$$

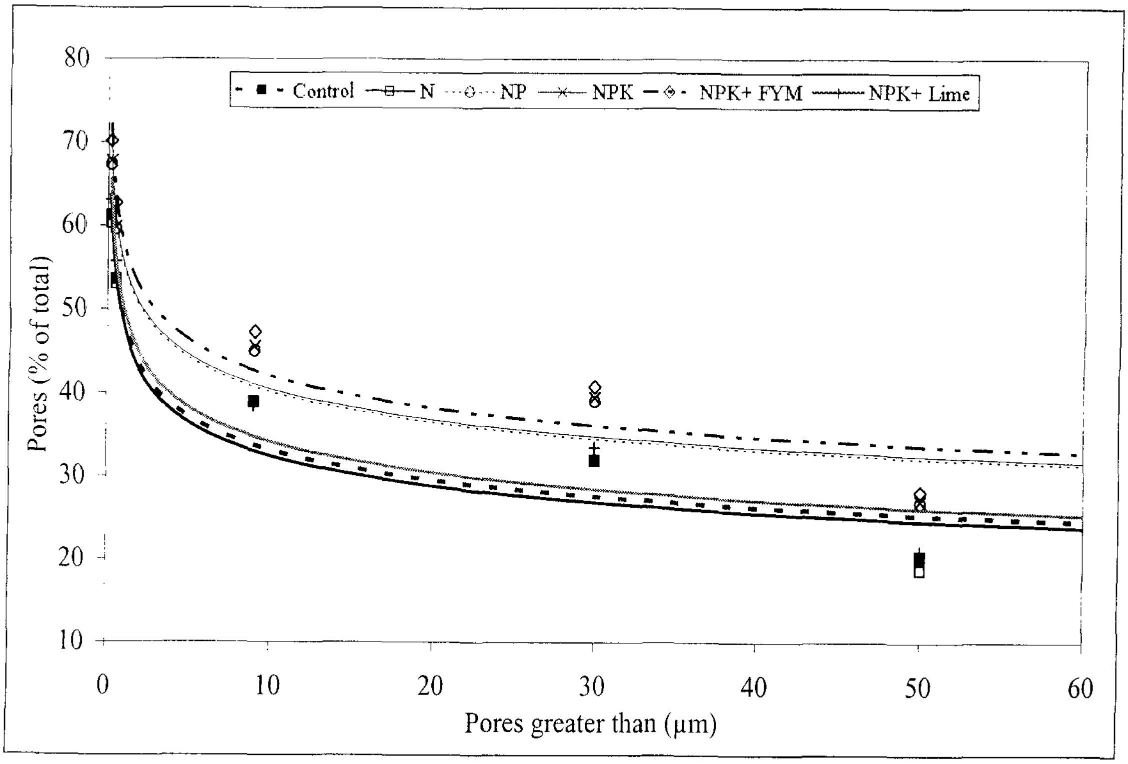


Figure 4.5 Effect of chemical fertilizers and amendments on pore-size distribution in 0-0.075 m soil layer

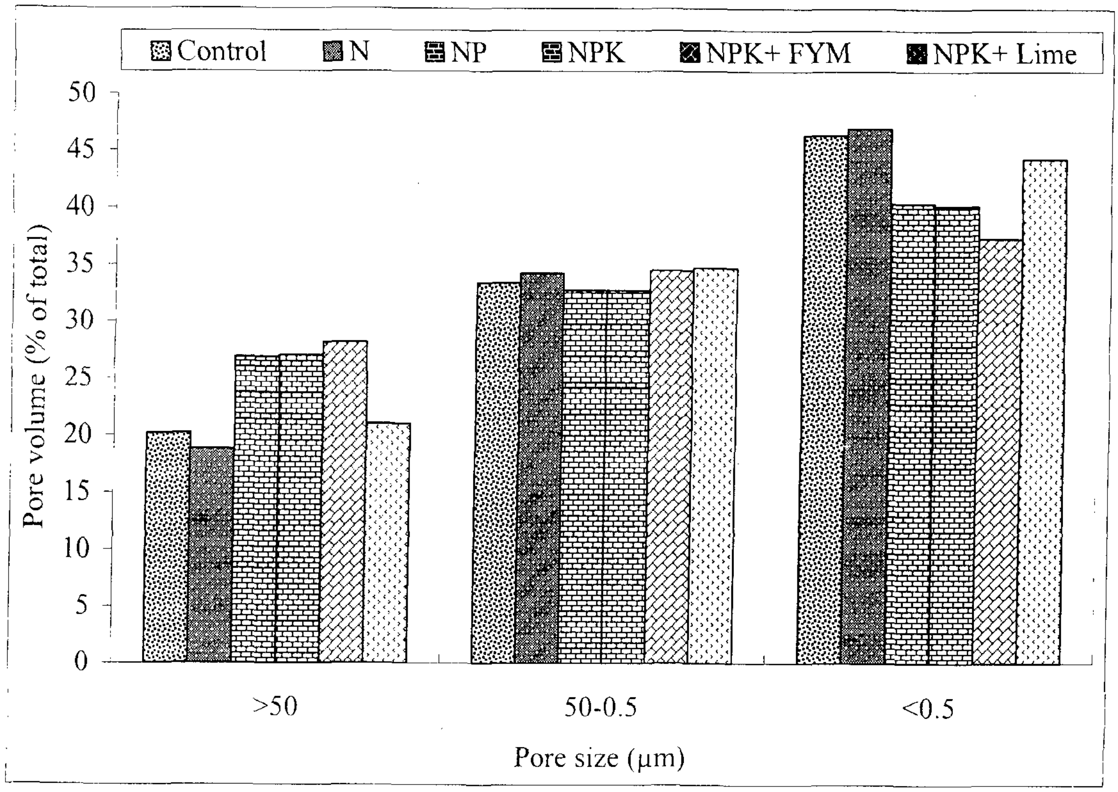


Figure 4.6 Effect of chemical fertilizers and amendments on water transmission (>50 μm), water storage (0.5-50 μm) and residual (<0.5 μm) pores in 0-0.075 m soil layer

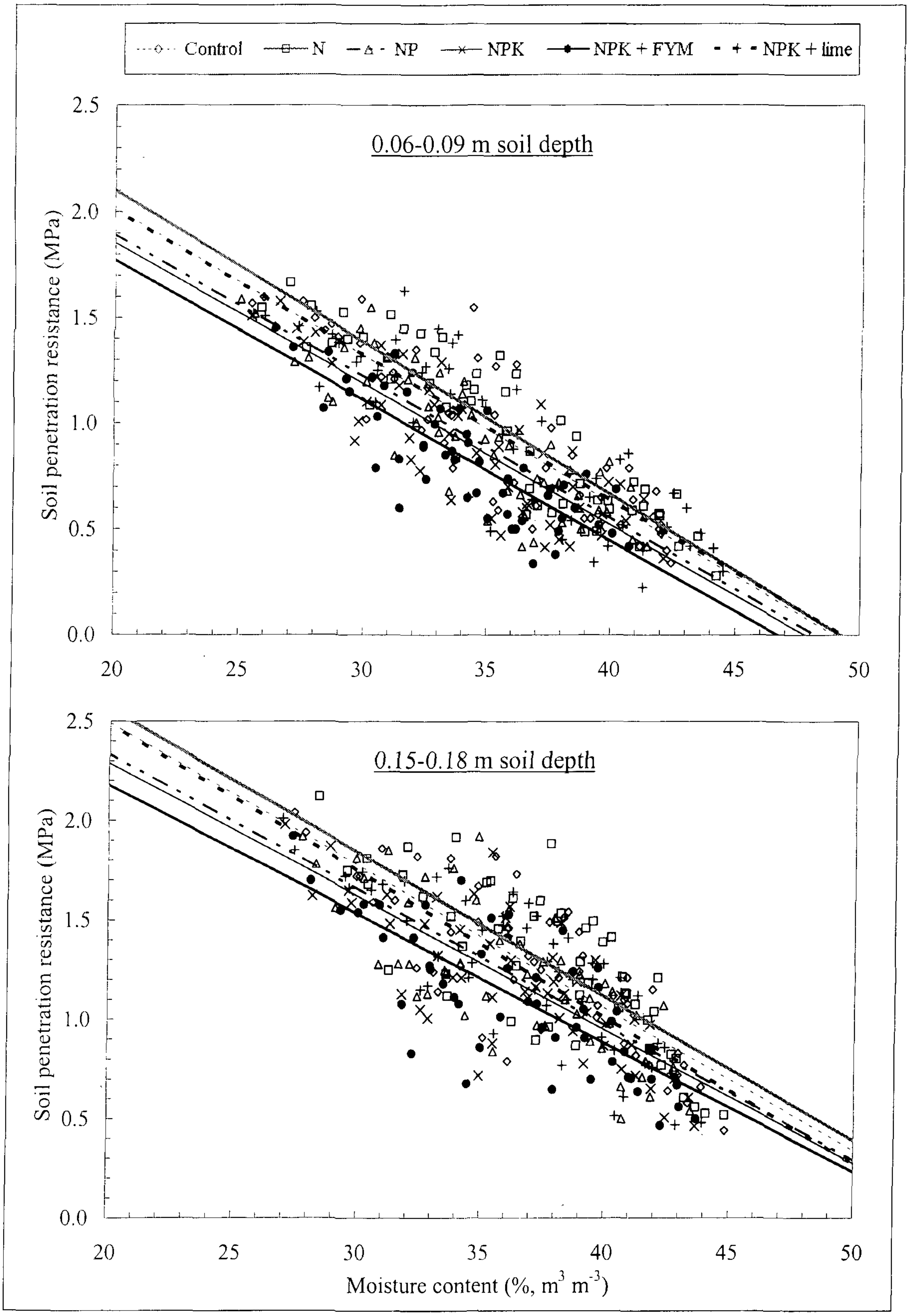


Figure 4.7 Effect of chemical fertilizers and amendments on soil penetration resistance as a function of moisture content

SPR (NPK + lime) $= 3.372 - 0.068\,\theta$; $R^2 = 0.768^{**}$ (4.6)

At 0.15 m soil depth: ($n = 52$, $27.0 \leq \theta \leq 44.8$)

SPR (Control) $= 3.923 - 0.072\,\theta$; $R^2 = 0.647^{**}$ (4.7)

SPR (N) $= 4.022 - 0.073\,\theta$; $R^2 = 0.605^{**}$ (4.8)

SPR (NP) $= 3.693 - 0.068\,\theta$; $R^2 = 0.598^{**}$ (4.9)

SPR (NPK) $= 3.631 - 0.067\,\theta$; $R^2 = 0.607^{**}$ (4.10)

SPR (NPK + FYM) $= 3.474 - 0.065\,\theta$; $R^2 = 0.595^{**}$ (4.11)

SPR (NPK + lime) $= 3.954 - 0.074\,\theta$; $R^2 = 0.677^{**}$ (4.12)

4.1.2.4 Hydraulic properties

a. Soil water retention and water availability

Soil water retention curves, determined in 0-0.075 m soil layer at wheat harvest (*rabi*, 2003-04) and expressed on mass and volume basis, are shown in Fig 4.8 (Appendix-XI). The water retention on mass basis was the lowest in N and highest in NPK + FYM plots; the respective values were 41.2 and 56.4% at 0 kPa, 28.0 and 33.4% at 10 kPa, and 16.3 and 16.8% at 1500 kPa (Table 4.6). Compared to control, the mass wetness at 0 and 10 kPa was higher with all the treatments, except N. At 1500 kPa suction, mass wetness was statistically at par in all the treatments, except NPK + FYM which showed the highest water retention.

The water retention on volume basis at 0, 10 and 1500 kPa suction was statistically the lowest in control (Table 4.6). The highest water retention was recorded under NPK + FYM at 0 and 10 kPa suction and under N at 1500 kPa suction.

The plant available water capacity (PAWC) on both mass and volume basis was higher with all treatments (except N) than control (Table 4.6). The PAWC varied between 11.6% in N and 16.6% in NPK + FYM on mass basis, and between 15.1% in N and 18.6% in NPK + FYM on volume basis. The PAWC on both mass and volume basis under different treatments followed the order; i.e. NPK + FYM > NPK > NP > NPK + lime > Control > N.

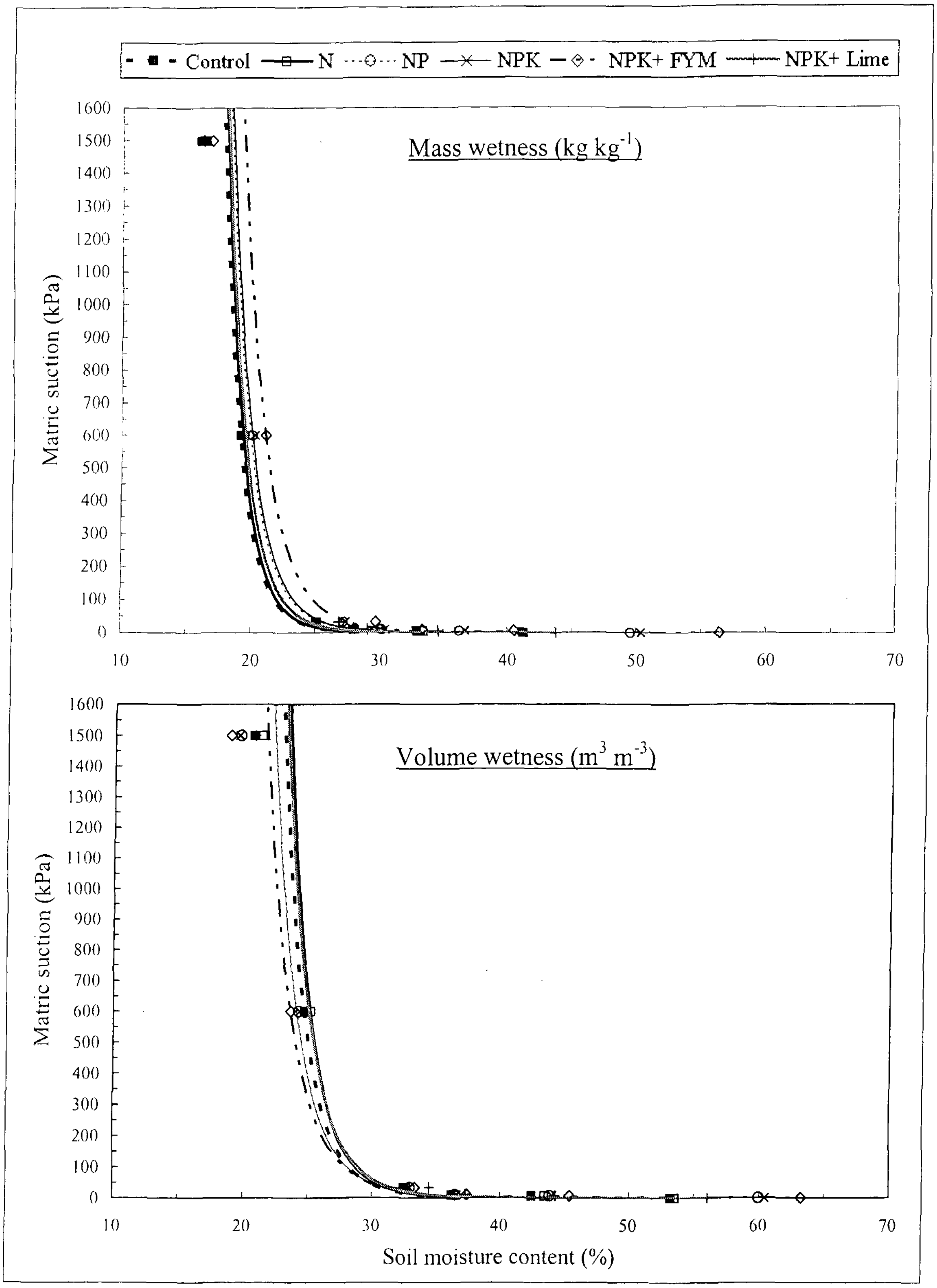


Figure 4.8 Effect of chemical fertilizers and amendments on soil moisture characteristics

Table 4.6 Effect of chemical fertilizers and amendments on soil water retention and plant available water capacity (PAWC)

Treatment	Mass wetness (%)			Volume wetness (%)			PAWC (%)	
	0 kPa	10 kPa	1500 kPa	0 kPa	10 kPa	1500 kPa	Mass basis	Volume basis
Control	41.2	28.1	16.0	53.2	36.2	20.6	12.1	15.6 (1.29)
N	41.2	28.0	16.3	53.5	36.4	21.2	11.6	15.1 (1.30)
NP	49.6	30.2	16.2	60.0	36.5	19.6	14.0	16.9 (1.21)
NPK	50.4	30.5	16.3	60.4	36.6	19.5	14.2	17.1 (1.20)
NPK + FYM	56.4	33.4	16.8	63.2	37.4	18.9	16.6	18.6 (1.12)
NPK + lime	43.8	29.1	16.2	56.1	37.3	20.7	13.0	16.6 (1.28)
LSD (P=0.05)	0.7	0.4	0.4	0.9	0.5	0.5	0.7	0.8

Note: Values in parenthesis indicate bulk density (Mg m^{-3}) of soil.

b. Infiltration

Different fertilizer and amendment combinations significantly affected the infiltration characteristics measured after maize harvest (*kharif*, 2004) (Fig. 4.9, Appendix-XII). Kostiakov-Lewis constants are presented in Table 4.7. Higher values of 'k' constant indicate greater water intake into the soil. The 'k' and 'a' constants varied from 4.49 to 7.33 and 0.535 to 0.596 in N and NPK + FYM treatments, respectively.

The steady-state infiltration rate (*i*) under different treatments is shown in Table 4.8. The N, control and NPK + lime recorded the lowest '*i*' (3.49 x 10^{-6} – 3.81 x 10^{-6} m s^{-1}), while NPK + FYM recorded the highest value (7.44 x 10^{-6} m s^{-1}). Application of NP and NPK resulted in an increase in '*i*' by about 50 and 56%, respectively, over the control. The NPK + FYM increased '*i*' over control by about 104%. Addition of FYM to NPK increased '*i*' by about 31%, while addition of lime to NPK decreased '*i*' by 33% over NPK. The infiltration rate under different treatments statistically followed the order: NPK + FYM > NPK = NP > NPK + lime = Control = N.

The steady-state infiltration rate was arrived in about 6 hours in all the treatments. Cumulative infiltration (*I*) after about six hours varied between 0.11 m in control and 0.24 m in NPK + FYM (Table 4.8). The treatment effects on '*I*' were similar to

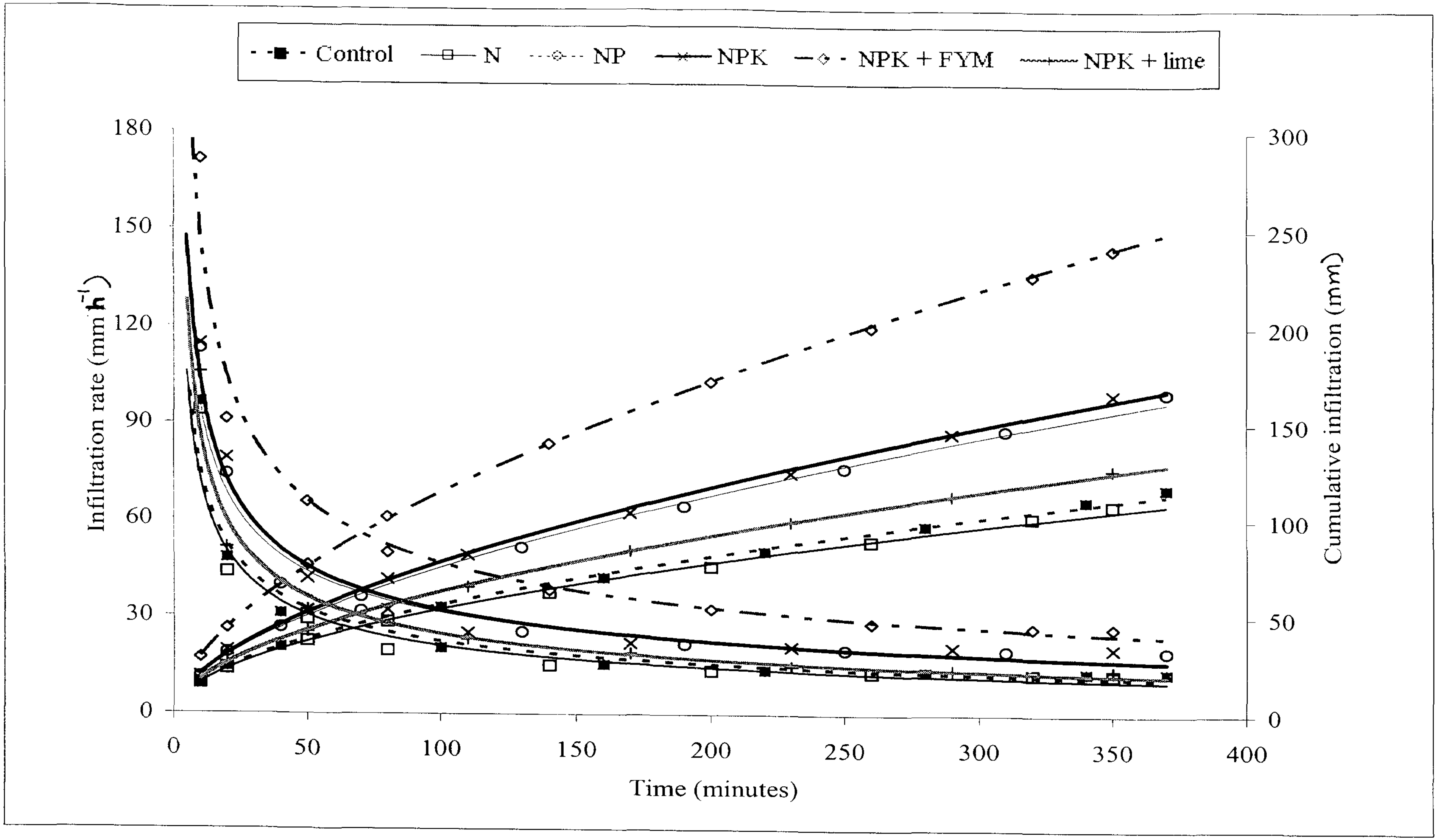


Figure 4.9 Effect of chemical fertilizers and amendments on infiltration characteristics of soil under maize-wheat cropping

those on infiltration rate, and statistically followed the order: NPK + FYM > NPK = NP > NPK + lime = Control = N.

Table 4.7 Effect of chemical fertilizers and amendments on Kostiakov-Lewis constants

Treatment	Kostiakov-Lewis constants		R^2
	k	a	
Control	4.66	0.539	0.986
N	4.49	0.535	0.934
NP	5.08	0.585	0.993
NPK	5.24	0.586	0.994
NPK + FYM	7.33	0.596	0.999
NPK + lime	4.93	0.552	0.994

c. Saturated hydraulic conductivity

The saturated hydraulic conductivity (K_S) under different treatments varied between 3.99 x 10^{-6} m s^{-1} (N) and 18.57 x 10^{-6} m s^{-1} (NPK + FYM) (Table 4.8). All the treatments, except N, had significantly higher K_S than control (4.59 x 10^{-6} m s^{-1}). The NPK showed about 2.8 times higher K_S than N and 2.4 times higher K_S than control. Application of FYM along with NPK further increased the K_S by about 1.7 times over NPK.

Table 4.8 Effect of chemical fertilizers and amendments on infiltration rate (*i*), cumulative infiltration (*I*), saturated hydraulic conductivity (K_S) and water subsidence rate

Treatment	*i* (x 10^{-6} m s^{-1})	*I* (m)	K_S (x 10^{-6} m s^{-1})	Water subsidence rate (x 10^{-6} m s^{-1})
Control	3.65	0.12	4.59	5.50
N	3.49	0.11	3.99	4.44
NP	5.47	0.17	9.96	10.56
NPK	5.70	0.17	11.14	11.11
NPK + FYM	7.44	0.24	18.57	20.56
NPK + lime	3.81	0.13	6.98	7.23
LSD (P=0.05)	0.48	0.01	2.19	1.72

d. Water subsidence rate

The treatment effects on the rate of water subsidence in maize plots during rainy season were almost similar to those in case of infiltration rate and saturated hydraulic conductivity (Table 4.8). The water subsidence rate varied between 4.44 x 10^{-6} m s^{-1} in N and 20.56 x 10^{-6} m s^{-1} in NPK + FYM. The various treatments statistically followed the order: NPK + FYM > NPK = NP > NPK + lime > Control = N.

e. *In-situ* layer-wise water percolation

In-situ water percolation at 0-0.25 m depth at every 0.05 m depth interval during maize cropping season is presented in Fig. 4.10 (Appendix-XIII). The surface 0-0.05 m layer was the most permeable under all the treatments; soil permeability decreased with depth. Further, while in N, NP, NPK and NPK + FYM the least permeable layer was 0.15-0.20 m, it was 0.10-0.15 m layer in control and NPK + lime. Percolation in least permeable layer under different treatments was about half to one-fifth of that in surface 0.05 m layer; the highest reduction was observed in N and control plots. Soil permeability in general was the highest in NPK + FYM, followed by NPK, NP, NPK + lime, control and N.

f. Soil-water contact angle

Soil water contact angle was significantly affected by different treatments (Table 4.9). Soil water contact angle varied between 58.57^0 in control and 63.65^0 in NPK + FYM. The NPK + lime with a soil water contact angle of 59.40^0 was at par with control. The N, NP and NPK increased the soil water contact angle to 61.14^0, 61.42^0 and 61.74^0, and all values were statistically at par.

Table 4.9 Effect of chemical fertilizers and amendments on soil-water contact angle

Treatment	Soil-water contact angle (degrees)
Control	58.57
N	61.14
NP	61.42
NPK	61.74
NPK + FYM	63.65
NPK + lime	59.40
LSD (P=0.05)	1.50

According to these data, application of chemical fertilizers increased the soil-water contact angle; the effect being more pronounced with the application of FYM. Application of lime, on the other hand resisted change in soil-water contact angle.

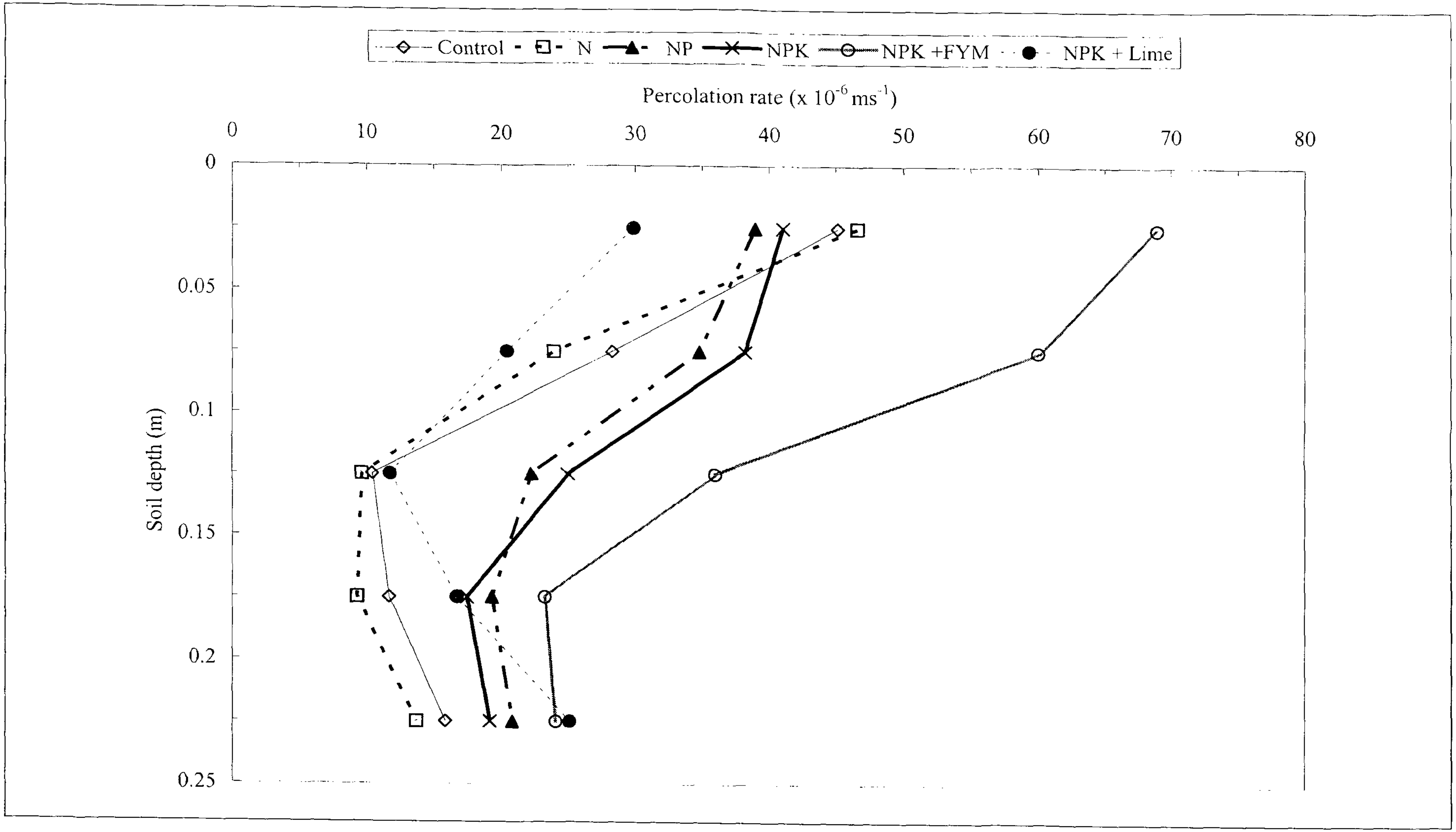


Figure 4.10 Effect of chemical fertilizers and amendments on water percolation at different soil depths under maize-wheat cropping

4.1.2.5 Mechanical properties

a. Consistency limits

Continuous application of fertilizers and amendments for 32 years showed significant effect on the soil consistency limits viz. liquid limit (LL), plastic limit (PL), plasticity index (PI), shrinkage limit (SL) and friability range (FR) (Table 4.10). The LL varied between 34.2% in control and 37.7% in NPK + FYM; PL varied between 25.0% in control and 27.1% in NPK + FYM; SL varied between 15.9% in control and 19.2% in NPK + FYM; PI varied between 9.2% in control and 10.6% in NPK + FYM; and FR varied between 7.9% in NPK + FYM and 9.6% in N. The LL, PL, SL and PI were statistically the highest in NPK + FYM and the lowest in control. The LL and PL were statistically the same in N and NPK + FYM. The PI was at par with N, NP, NPK and NPK + FYM. The FR, on the other hand, was highest (9.1-9.6%) in control and N, followed by NP, NPK and NPK + lime (8.2-8.6%), and lowest in NPK + FYM (7.9%). The LL, PL, SL, PI and FR were at par with NP and NPK treatments.

Table 4.10 Effect of chemical fertilizers and amendments on consistency limits of soil

Treatment	Soil Moisture content (%)				
	LL	PL	SL	PI	FR
Control	34.2	25.0	15.9	9.2	9.1
N	36.9	26.5	17.0	10.4	9.6
NP	36.1	25.9	17.3	10.2	8.6
NPK	36.4	26.1	17.6	10.3	8.5
NPK + FYM	37.7	27.1	19.2	10.6	7.9
NPK + lime	36.2	26.0	17.8	10.1	8.2
LSD (P=0.05)	1.1	0.9	1.2	0.4	0.4

4.2 Crop water use

The profile-water use from 0-0.90 m soil depth during different phenological stages of wheat (2003-04 and 2004-05) is shown in Fig. 4.11 (Appendix XIV). The profile-water use at all phenological stages under study was minimum in N and maximum in NPK + FYM plots during both the years. It varied from 8.4 to 15.6 mm during sowing-tillering, -20.0 to 1.5 mm during tillering-flowering, 58.7 to 110.0 mm during flowering-

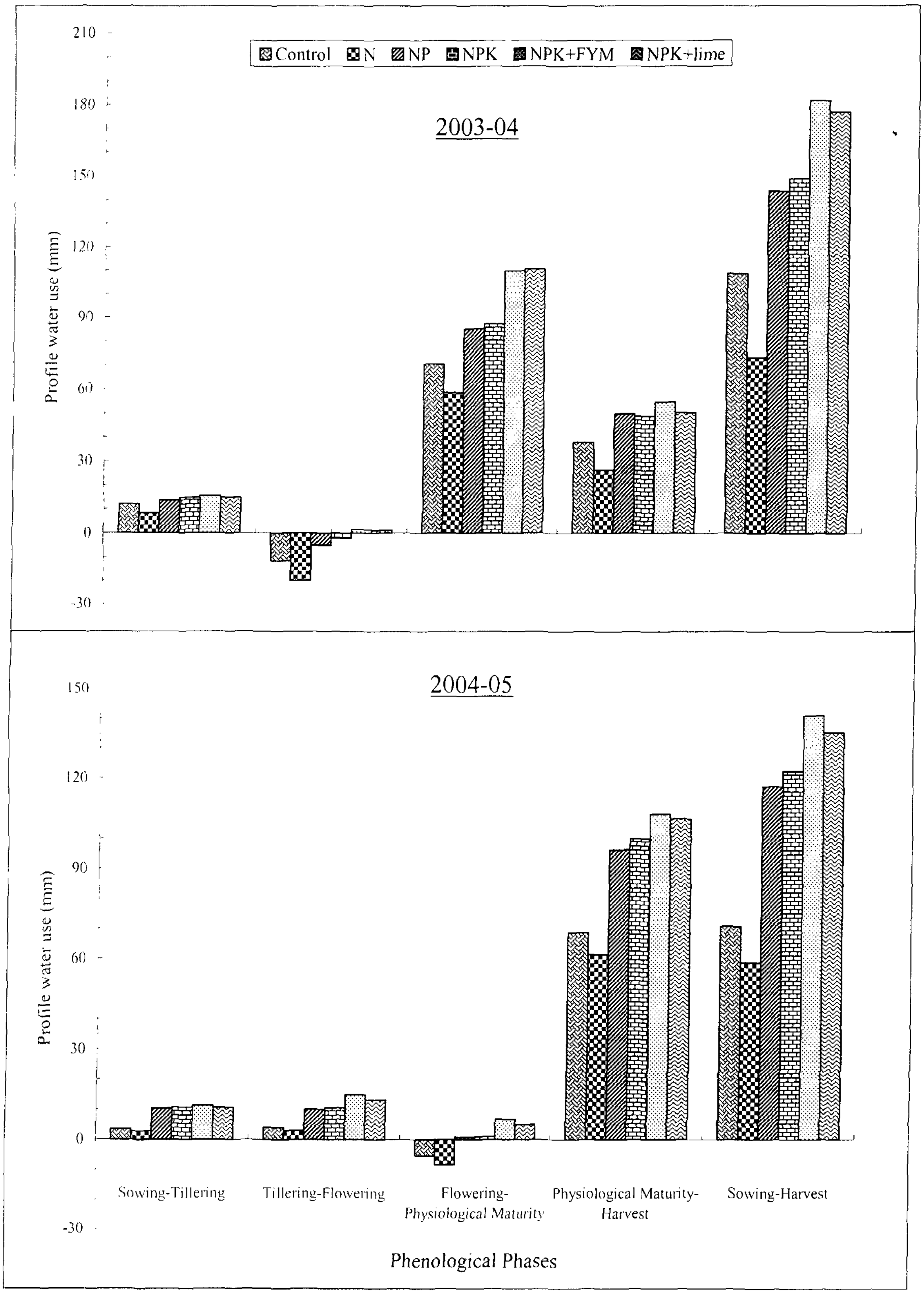


Figure 4.11 Effect of chemical fertilizers and amendments on profile water use during wheat season

physiological maturity, 26.4 to 54.8 mm during physiological maturity-harvest, and 73.5 to 181.9 mm during sowing-harvest in 2003-04. The corresponding values during 2004-05 were 2.8 to 11.2, 3.0 to 14.9, -8.5 to 6.7, 61.4 to 108.0 and 58.8 to 140.9 mm, respectively. During both the years, various treatments numerically followed the order: NPK + FYM > NPK + lime > NPK > NP > control > N.

Total water use (profile-water use + irrigation + rainfall) during different phenological stages of wheat (2003-04 and 2004-05) is shown in Fig. 4.12 (Appendix XIV). Like profile-water use, total water use in wheat was the lowest under N and highest under NPK + FYM. The corresponding values were 59.9 and 67.1 mm during sowing-tillering, 352.5 and 374.0 mm during tillering-flowering, 149.0 and 200.1 mm during flowering-physiological maturity, 28.5 and 56.9 mm during physiological maturity-harvest, and 589.9 and 698.3 mm during sowing-harvest in 2003-04. During 2004-05, the corresponding values were 88.8 and 97.2 mm during sowing-tillering, 518.3 and 530.2 mm during tillering-flowering, 111.4 and 126.6 mm during flowering-physiological maturity, 99.5 and 146.1 mm during physiological maturity-harvest, and 818.1 and 900.2 mm during sowing-harvest. Total water use was almost the same in NP and NPK, and NPK + lime and NPK + FYM.

4.3 Crop yields

4.3.1 Maize

The data pertaining to grain and stover yield of maize *(Kharif,* 2003 and 2004) are presented in Table 4.11. The N plots did not produce any grain yield of maize during both the years. Among other treatments, control produced significantly the lowest and NPK + FYM the highest maize grain yield; the values were 0.47 and 4.27 Mg ha^{-1} during 2003, and 0.58 and 6.03 Mg ha^{-1} during 2004, respectively. The maize yield increased progressively with NP, NPK, NPK + lime and NPK + FYM over control during both the years; the respective increase was 1.49, 2.09, 3.58 and 3.80 Mg ha^{-1} during 2003, and 2.45,

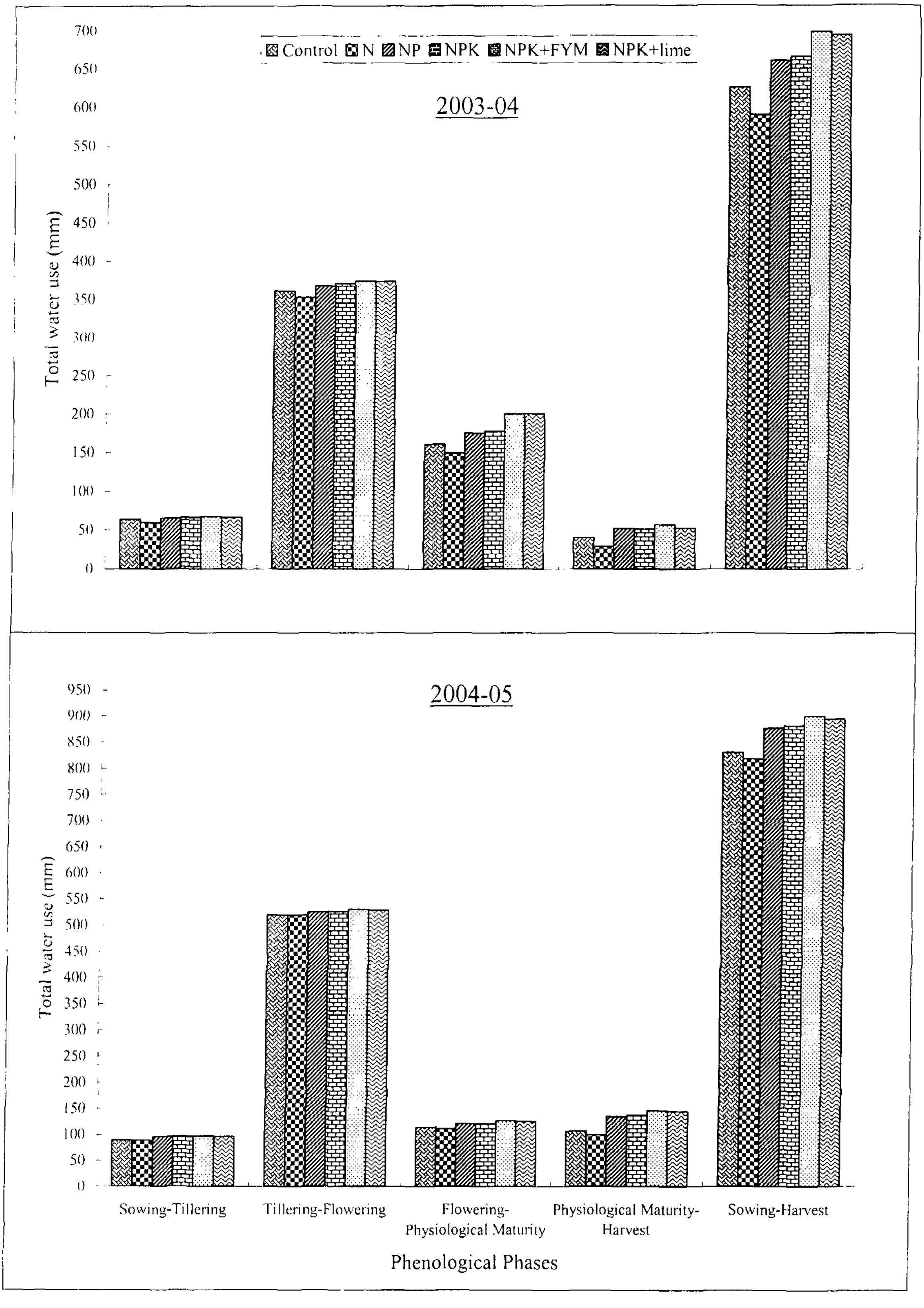


Figure 4.12 Effect of chemical fertilizers and amendments on total water use during wheat season

3.81, 4.72 and 5.45 Mg ha^{-1} during 2004.

Table 4.11 Effect of chemical fertilizers and amendments on grain and stover yield of maize

Treatment	Grain yield (Mg ha^{-1})		Stover yield (Mg ha^{-1})	
	2003	2004	2003	2004
Control	0.47	0.58	1.14	1.34
N	0.00	0.00	0.00	0.00
NP	1.96	3.03	4.96	4.25
NPK	2.56	4.39	6.38	7.18
NPK + FYM	4.27	6.03	10.39	10.17
NPK + lime	4.05	5.30	9.77	7.97
LSD (P=0.05)	0.50	0.50	1.00	1.01

The maize stover yield followed almost the same trend as maize grain yield during both the years. Maize stover yield was zero in N plots. In rest of the treatments, stover yield varied from 1.14 Mg ha^{-1} in control to 10.39 Mg ha^{-1} in NPK + FYM during 2003, and from 1.34 Mg ha^{-1} in control to 10.17 Mg ha^{-1} in NPK + FYM during 2004. The NP, NPK, NPK + lime and NPK + FYM applications resulted in an increase in stover yield by 3.82, 5.24, 8.63 and 9.25 Mg ha^{-1}, respectively, over control during 2003. The corresponding increase during 2004 was 2.91, 5.84, 6.63 and 8.83 Mg ha^{-1}, respectively.

4.3.2 Wheat

The data pertaining to grain and straw yield of wheat (2003-04 and 2004-05) are presented in Table 4.12. Wheat yield was also significantly affected by different treatments. Long-term application of N alone through urea reduced grain yield to zero. Grain yield in the rest of the treatments varied from 0.35 Mg ha^{-1} in control to 2.33 Mg ha^{-1} in NPK + FYM during 2003-04, and from 0.59 Mg ha^{-1} in control to 3.33 Mg ha^{-1} in NPK + FYM during 2004-05. The NPK + lime produced grain yields comparable to NPK + FYM, and both the treatments were significantly superior to the rest of the treatments. Application of NP, NPK, NPK + lime and NPK + FYM increased wheat grain yield over control by 0.75, 1.39, 1.97 and 1.98 Mg ha^{-1}, respectively, during 2003-04, and by 1.71, 2.12, 2.52 and 2.74 Mg ha^{-1}, respectively, during 2004-05.

Table 4.12 Effect of chemical fertilizers and amendments on grain and straw yield of wheat

Treatment	Grain yield (Mg ha^{-1})		Straw yield (Mg ha^{-1})	
	2003-04	2004-05	2003-04	2004-05
Control	0.35	0.59	0.63	1.75
N	0.00	0.00	0.00	0.00
NP	1.10	2.30	3.22	5.17
NPK	1.74	2.71	4.56	6.01
NPK + FYM	2.33	3.33	5.38	7.91
NPK + lime	2.32	3.11	5.23	6.88
LSD (P=0.05)	0.26	0.56	0.46	0.97

Wheat straw yield followed almost similar trend as wheat grain yield (Table 4.12). Wheat straw production with N was zero. Among other treatments, straw production varied from 0.63 Mg ha^{-1} in control to 5.38 Mg ha^{-1} in NPK + FYM during 2003-04, and from 1.75 Mg ha^{-1} in control to 7.91 Mg ha^{-1} in NPK + FYM during 2004-05. The NP, NPK, NPK + lime and NPK + FYM increased straw production over control by 2.59, 3.93, 4.60 and 4.75 Mg ha^{-1}, respectively, during 2003-04, and 3.42, 4.26, 5.13 and 6.16 Mg ha^{-1}, respectively, during 2004-05.

4.3.3 Maize-wheat system productivity

Data pertaining to total (grain) productivity of maize-wheat system are presented in Table 4.13. System productivity was zero with N treatment. System productivity varied from 0.82 Mg ha^{-1} in control to 6.59 Mg ha^{-1} in NPK + FYM during 2003-04, and from 1.17 Mg ha^{-1} in control to 9.36 Mg ha^{-1} in NPK + FYM during 2004-05. System productivity with NPK + lime was at par with NPK + FYM during 2003-04, but lower during 2004-05. Omission of potassium in nutrition (i.e. NP) caused a decline in system productivity over NPK by 1.24 and 1.78 Mg ha^{-1} during 2003-04 and 2004-05, respectively. The NPK + FYM increased the system productivity over NPK by 53% and over control by 704% during 2003-04. The corresponding values during 2004-05 were 32 and 700%, respectively.

Table 4.13 Effect of chemical fertilizers and amendments on maize-wheat system productivity

Treatment	'Maize+Wheat' grain yield (Mg ha^{-1})	
	2003-04	2004-05
Control	0.82	1.17
N	0.00	0.00
NP	3.06	5.32
NPK	4.30	7.10
NPK + FYM	6.59	9.36
NPK + lime	6.37	8.40
LSD (P=0.05)	0.66	0.93

4.4 Validation of DSSAT model

The "Decision Support System for Agrotechnology Transfer" (DSSAT v 3.5) model was tested for the prediction of wheat yield and soil moisture content under different fertilizer and amendment treatments.

4.4.1 Wheat yield

The observed and simulated wheat grain yields under different treatments for 2004-05 are shown in Table 4.14. The model estimated the grain yields close to the observed values in NPK + FYM and NPK + lime, while over-estimated in all other treatments. Nevertheless, the trend in simulated wheat yields under different treatments was the same as in observed yields, except in N. The root mean square error for observed and simulated yield was 1.64.

Table 4.14 Observed and simulated grain yield of wheat (2004-05) under different treatments

Treatment	Wheat grain yield (Mg ha^{-1})	
	Observed	Simulated
Control	0.59	2.14
N	0.00	3.43
NP	2.30	3.45
NPK	2.71	3.46
NPK + FYM	3.33	3.50
NPK + Lime	3.11	3.47

4.4.2 Soil moisture

The simulated and observed values for soil moisture content under different treatments during wheat season (2004-05) are presented in Tables 4.15a and 4.15b.

The model underestimated the moisture content in the surface layer (0-0.05 m) at all the phenologoical stages of wheat compared to the observed values, indicating the highest moisture loss at soil surface. The layer-wise simulated soil moisture contents at 0.05-0.90 m soil depth were also lower than the observed ones at all the phenological stages, except at harvest where the trend was reversed i.e simulated moisture contents were higher than the observed ones. The deviations from the observed data were relatively higher in the upper soil layers as indicated by the root mean square error (RMSE) values. The RMSE among different treatments varied between 0.047 and 0.077 for the 0-0.05 m layer, 0.049-0.074 for 0.05-0.15 m layer, 0.049-0.066 for 0.15-0.30 m layer, 0.046-0.066 in 0.30-0.45 m layer, 0.031-0.056 in 0.45-0.60 m layer and 0.042-0.052 for 0.60-0.90 m layer (Appendix-XV).

The observed and simulated values of soil moisture content, averaged over 0-0.90 m soil depth, at different phenological stages of wheat (2004-05) are presented in Fig. 4.13 (Appendix-XVI). The model under-estimated the moisture contents upto physiological maturity, while over-estimated between physiological maturity and crop harvest.

4.5 Non-limiting water range

The non-limiting water range (NLWR) was determined during the wheat season using the values of air-filled porosity and soil penetration resistance at 0.15-0.18 m soil depth. The effect of different cropping systems, chemical fertilizers and organic amendments on NLWR, plant available water capacity (PAWC) and NLWR:PAWC ratio are shown in Tables 4.16 to 4.18. Higher the value of NLWR and NLWR:PAWC ratio, better is the physical productivity of soil.

Table 4.15a Observed and simulated values of soil moisture content during wheat season (2004-05)

Treatment	Soil depth (m)											
	0-0.05		0.05-0.15		0.15-0.30		0.30-0.45		0.45-0.60		0.60-0.90	
	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.
	Tillering stage											
Control	0.188	0.275	0.253	0.305	0.286	0.380	0.305	0.390	0.314	0.373	0.309	0.373
N	0.213	0.279	0.279	0.310	0.309	0.382	0.315	0.395	0.319	0.377	0.309	0.367
NP	0.164	0.258	0.246	0.287	0.283	0.358	0.304	0.387	0.313	0.381	0.307	0.373
NPK	0.169	0.262	0.250	0.291	0.276	0.344	0.304	0.377	0.313	0.368	0.307	0.360
NPK + FYM	0.172	0.254	0.257	0.282	0.280	0.347	0.303	0.389	0.313	0.388	0.307	0.374
NPK + lime	0.166	0.285	0.247	0.316	0.277	0.351	0.304	0.375	0.313	0.367	0.307	0.370
	Flowering stage											
Control	0.239	0.290	0.273	0.323	0.296	0.374	0.316	0.382	0.326	0.358	0.315	0.365
N	0.271	0.295	0.305	0.328	0.330	0.388	0.339	0.382	0.343	0.353	0.326	0.364
NP	0.234	0.275	0.260	0.305	0.283	0.349	0.301	0.368	0.311	0.344	0.307	0.363
NPK	0.240	0.271	0.265	0.301	0.276	0.326	0.301	0.359	0.311	0.343	0.307	0.350
NPK + FYM	0.251	0.266	0.274	0.295	0.279	0.331	0.300	0.356	0.311	0.345	0.306	0.364
NPK + lime	0.238	0.295	0.263	0.327	0.277	0.335	0.301	0.342	0.311	0.341	0.307	0.358

Table 4.15b Observed and simulated values of soil moisture content during wheat season (2004-05)

Treatment	Soil depth (m)											
	0-0.05		0.05-0.15		0.15-0.30		0.30-0.45		0.45-0.60		0.60-0.90	
	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.
	Physiological maturity											
Control	0.198	0.323	0.290	0.359	0.302	0.379	0.311	0.368	0.319	0.364	0.308	0.366
N	0.239	0.341	0.321	0.378	0.342	0.390	0.331	0.375	0.328	0.358	0.308	0.367
NP	0.198	0.278	0.263	0.309	0.287	0.351	0.303	0.365	0.312	0.349	0.307	0.357
NPK	0.202	0.274	0.267	0.305	0.280	0.327	0.303	0.356	0.312	0.342	0.306	0.347
NPK + FYM	0.210	0.263	0.274	0.292	0.284	0.321	0.303	0.353	0.312	0.341	0.306	0.352
NPK + lime	0.201	0.293	0.265	0.325	0.281	0.328	0.303	0.340	0.312	0.338	0.306	0.348
	Harvest											
Control	0.101	0.133	0.246	0.148	0.285	0.268	0.304	0.324	0.313	0.340	0.307	0.333
N	0.113	0.164	0.266	0.182	0.310	0.281	0.315	0.340	0.318	0.339	0.307	0.342
NP	0.099	0.106	0.235	0.118	0.278	0.222	0.301	0.256	0.311	0.263	0.306	0.294
NPK	0.102	0.107	0.239	0.119	0.271	0.207	0.301	0.242	0.311	0.249	0.306	0.269
NPK + FYM	0.108	0.104	0.248	0.115	0.275	0.193	0.300	0.224	0.311	0.234	0.306	0.262
NPK + lime	0.100	0.117	0.237	0.130	0.272	0.195	0.301	0.226	0.311	0.232	0.306	0.266

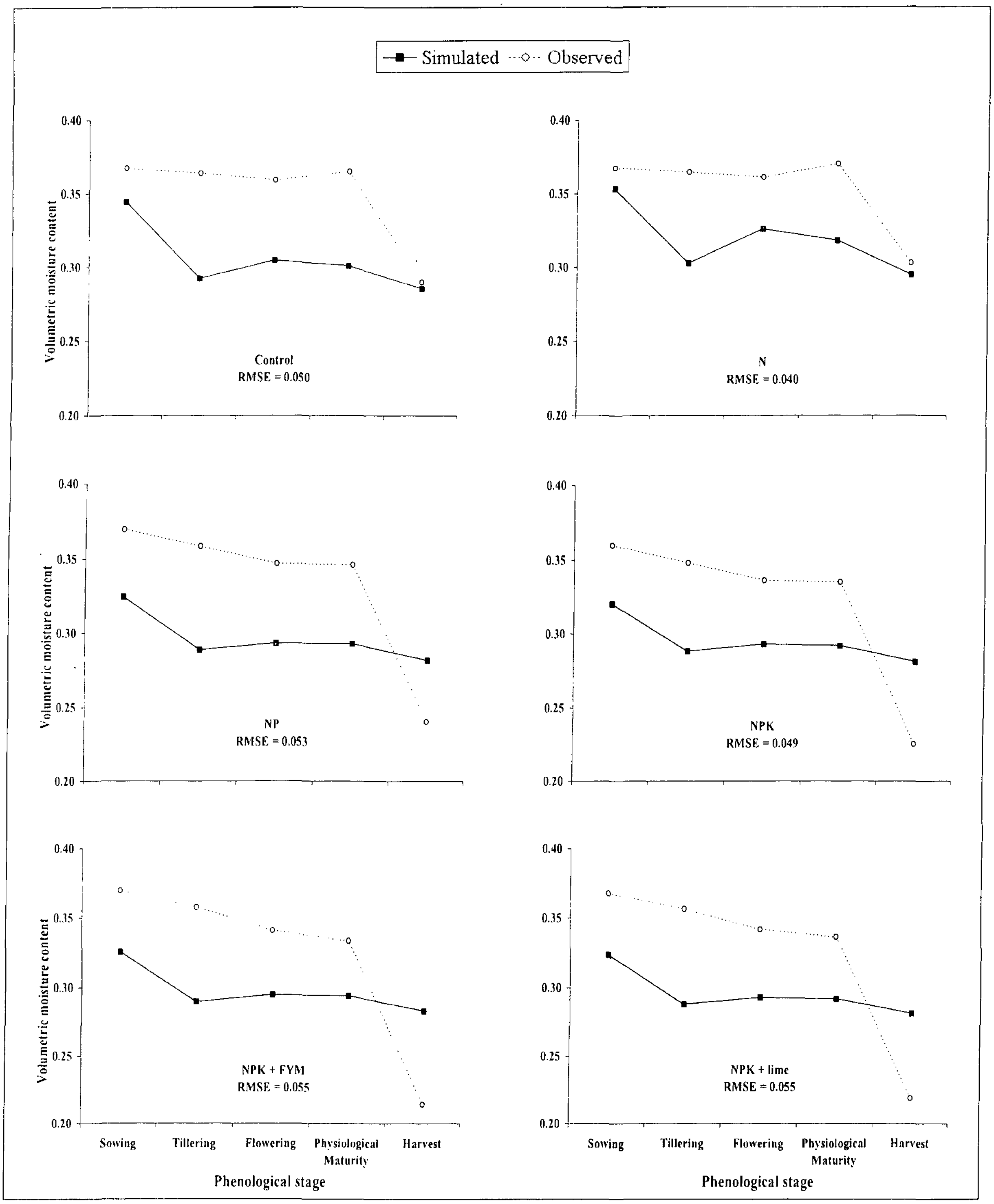


Figure 4.13 Observed and simulated (DSSAT v 3.5) volumetric moisture content under different treatments at different phenological stages of wheat (2004-05)

4.5.1 Effect of cropping systems

The volumetric moisture contents corresponding to 10% air-filled porosity and 2 MPa soil penetration resistance (SPR), and NLWR, PAWC and NLWR:PAWC ratio determined under different cropping systems are presented in Table 4.16.

The moisture content corresponding to 10% air-filled porosity was highest in soybean-wheat (40.7%), followed by grasses (39.8-40.6%), maize-wheat (37.5-39.2%) and lowest in rice-wheat (34.6-37.4%). The moisture content corresponding to 2 MPa SPR was lowest in soybean-wheat (23.9%) and maize-wheat (23.8-24.3%), followed by grasses (25.0-25.4%), and highest in rice-wheat (26.1-27.6%).

The NLWR was highest in soybean-wheat (16.8%), followed by grasses (14.4-15.6%) and maize-wheat (13.1-15.4%), and lowest in rice-wheat (7.5-11.0%).

The PAWC in maize-wheat (17.1-17.9%), soybean-wheat (17.3%) and grasses (16.2-17.0%) was almost the same, but higher than in rice-wheat (14.1-16.1%) system.

Table 4.16 Long-term effects of different cropping systems on non-limiting water range (NLWR), plant available water capacity (PAWC) and NLWR:PAWC ratio

Cropping System	Duration (years)	θ (%, m^3m^{-3})		NLWR (%)	PAWC (%)	NLWR: PAWC
		10% *fa**	2 MPa SPR$^\$$			
Maize-wheat	32	37.5	24.3	13.1	17.1	0.77
Maize-Wheat	13	39.2	23.8	15.4	17.9	0.87
Soyabean-Wheat	18	40.7	23.9	16.8	17.3	0.97
Rice-Wheat	18	34.6	27.1	7.5	14.1	0.54
Rice-Wheat	14	36.9	26.8	10.2	15.8	0.64
Rice-Wheat	6	37.0	26.1	11.0	16.1	0.68
Rice-Wheat	6	37.4	27.6	9.8	15.9	0.62
Guinea grass	7	39.8	25.4	14.4	16.2	0.89
Setaria grass	6	40.6	25.0	15.6	17.0	0.92

* Air-filled porosity
$ Soil penetration resistance

The NLWR:PAWC ratio was highest in soybean-wheat (0.97), followed by grasses (0.89-0.92), maize-wheat (0.77-0.87), and lowest in rice-wheat (0.54-0.68).

According to NLWR and NLWR:PAWC ratio, soybean-wheat supported better soil physical conditions than other cropping systems under study; the poorest soil physical conditions were observed under rice-wheat system.

4.5.2 Effect of chemical fertilizers

The data on the influence of chemical fertilizers on NLWR, PAWC and NLWR:PAWC ratio under maize-wheat and rice-wheat cropping systems are presented in Table 4.17.

The moisture content at 10% air-filled porosity varied between 35.4 and 37.5% in N and NPK, respectively, under maize-wheat system. The N and NPK + lime were statistically at par with control with a value of 35.7%, and significantly lower than NP and NPK. The moisture content at 2 MPa SPR was lowest in NPK (24.3%) and highest in N (27.7%). Similarly, in the rice-wheat system, the moisture content in NPK corresponding to 10% air-filled porosity was higher (36.9%) and corresponding to 2 MPa SPR was lower (26.8%) than control with corresponding values of 34.1 and 27.9%, respectively.

The NLWR ranged between 7.7% (N) and 13.1% (NPK) in the maize-wheat system. The NLWR with N was lower, with NPK + lime was same, while with NP and NPK was higher than the NLWR in control. The application of NP and NPK increased NLWR by about 1.35 and 1.45 times, respectively, over the control. Under rice-wheat system, the NLWR with NPK increased by about 1.6 times over the control (6.2%).

The PAWC varied between 15.3% in control and 17.0% in NPK treatment under maize-wheat cropping sequence. The control, N and NPK + lime were at par with each other with values of 15.3, 15.9 and 16.0%, respectively. Under rice-wheat system, the NPK increased the PAWC from 14.0% in control to 15.8%.

The NLWR:PAWC ratio in maize-wheat system was the lowest in N (0.48), followed in increasing order by control and NPK + lime (each 0.59), NP (0.72) and NPK (0.77) treatments. This ratio in control was at par with NPK + lime; NP and NPK were also statistically at par with each other. Under rice-wheat system also the recommended dose of

Table 4.17 Long-term effects of chemical fertilizers on non-limiting water range (NLWR), plant available water capacity (PAWC) and NLWR:PAWC ratio under maize-wheat and rice-wheat cropping systems

Cropping System	Duration (years)	Treatments	θ (%, m^3m^{-3})		NLWR (%)	PAWC (%)	NLWR:PAWC
			10% f_a*	2 MPa SPR$^{\$}$			
Maize-Wheat	32	Control	35.7	26.7	9.0	15.6	0.58
		100% N	35.4	27.7	7.7	15.7	0.49
		100% NP	37.1	24.9	12.2	16.9	0.72
		100% NPK	37.5	24.3	13.1	17.1	0.77
		100% NPK + lime	35.9	26.5	9.4	16.2	0.58
LSD(P=0.05)			0.8	1.0	1.2	0.6	0.06
Rice-Wheat	14	Control	34.1	27.9	6.2	14.0	0.44
		100%NPK	36.9	26.8	10.2	15.8	0.64

* Air-filled porosity,

$ Soil penetration resistance

NPK increased the NLWR:PAWC ratio to 0.64 in comparison to 0.44 in control.

According to these data, application of NPK in balanced ratio maintained better soil physical conditions than NP, N and absolute control under both the cropping systems.

4.5.3 Effect of organic amendments

The effect of application of organics along with chemical fertilizers on NLWR, PAWC and NLWR:PAWC ratio under maize-wheat and rice-wheat cropping system are presented in Table 4.18.

Application of organics increased the moisture content at 10% air-filled porosity and decreased the moisture content corresponding to 2 MPa SPR, and thus increased the NLWR in both maize-wheat and rice-wheat systems, except in plots with no-tillage under rice-wheat system. No-tillage decreased the moisture content corresponding to 10% air-filled porosity and increased the moisture content corresponding to 2 MPa SPR, and thus decreased the NLWR. Under maize-wheat system, the NLWR in NPK + FYM was about 1.26 times higher than in NPK. Similarly, under rice-wheat system the NLWR increased by about 1.21-1.69 times in different experiments. Application of organics increased the PAWC and NLWR:PWAC ratio in both maize-wheat and rice-wheat systems.

4.5.4 Relationship between NLWR and wheat yield

The NLWR was linearly, positively and significantly correlated with grain yield of wheat under maize-wheat cropping (Fig. 4.14, Appendix-XVII). The following relationship between NLWR (%, soil moisture) and grain yield of wheat (GY, Mg ha^{-1}) was obtained ($n = 24$, $7.10 \leq \text{NLWR} \leq 18.94$):

During 2003-04 $GY = 0.191\ NLWR - 0.855$ $r = 0.646^{**}$ (4.13)

During 2004-05 $GY = 0.298\ NLWR - 1.373$ $r = 0.706^{**}$ (4.14)

4.6 Carbon management index

Carbon management index (CMI), which takes into account the changes in both

Table 4.18 Long-term effects of chemical fertilizers and organics on non-limiting water range (NLWR), plant available water capacity (PAWC) and NLWR:PAWC ratio under maize-wheat and rice-wheat cropping systems

Cropping System	Duration (years)	Treatments	θ (%, m^3m^{-3})		NLWR (%)	PAWC (%)	NLWR:PAWC
			10% f_a*	2 MPa SPR$^\$$			
Maize-Wheat	32	100% NPK	37.5	24.3	13.1	17.1	0.77
		100% NPK + FYM	39.2	22.7	16.5	18.0	0.92
Rice-Wheat	18	100%NK	34.6	27.1	7.5	14.1	0.54
		100%NK + Lantana	37.1	24.3	12.7	15.7	0.82
Rice-Wheat	14	100%NPK	36.9	26.8	10.2	15.8	0.64
		50%NPK + FYM	38.0	25.0	13.1	17.2	0.76
		50%NPK + Wheat straw	37.2	25.8	11.4	16.2	0.70
Rice-Wheat	6	100%NPK	37.0	26.1	11.0	16.1	0.68
		100%NPK + Lantana§	36.9	26.3	10.5	15.3	0.69
Rice-Wheat	6	100%NPK	37.4	27.6	9.8	15.9	0.62
		75%N100%PK + 25% N through Lantana	38.3	26.4	11.9	17.2	0.69

* Air-filled porosity,
$ Soil penetration resistance
§ No-tillage for wheat

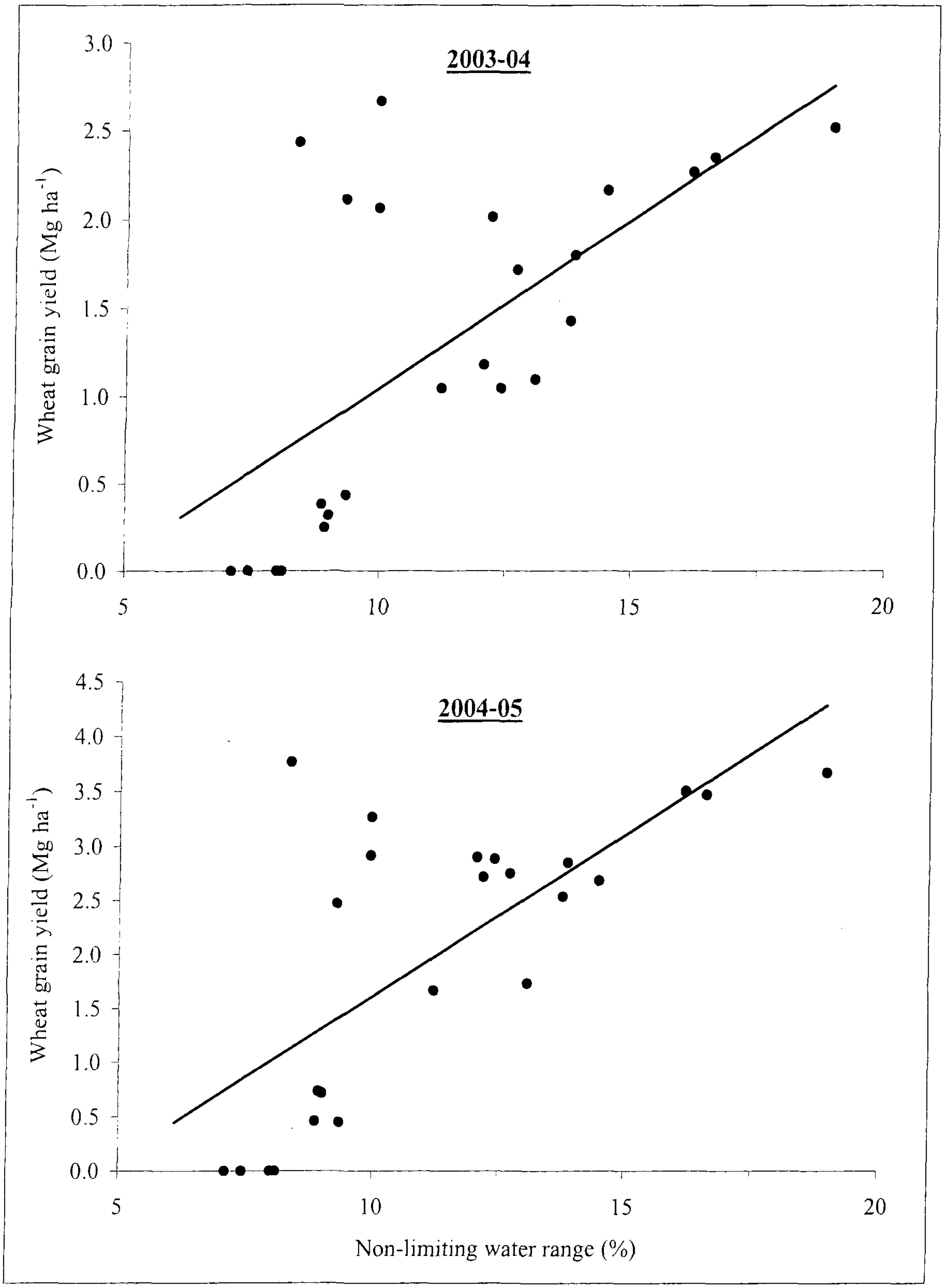


Figure 4.14 Relationship between non-limiting water range and wheat grain yield

total carbon and labile carbon, measures soil sustainability. A system is sustainable if CMI $\geq$ 100 (Blair *et al.*, 1995). The data on the effect of different cropping systems, chemical fertilizers and organic amendments on total carbon (C_T), labile carbon (C_L), non-labile carbon (C_{NL}), lability index (LI), carbon pool index (CPI) and carbon management index (CMI) in the 0-0.15 m soil layer samples are shown in Tables 4.19 to 4.21.

4.6.1 Effect of cropping systems

The data on the effect of different cropping systems on carbon pools and carbon management index are presented in Table 4.19.

Total carbon (C_T): The C_T varied from 1.59% under rice-wheat system (14 years) to 4.29% under setaria grass system. The C_T was highest among grasses followed by soybean-wheat, maize-wheat and rice-wheat systems, with mean values of 4.21, 3.02, 2.91 and 2.49%, respectively.

Labile carbon (C_L): The C_L varied from 1.23 mg kg^{-1} under rice-wheat (14 years) to 3.89 mg kg^{-1} under guinea grass system. As in C_T, the C_L was highest under grasses, followed by soybean-wheat, maize-wheat and rice-wheat systems, with mean values of 3.81, 2.13, 2.01 and 1.77 mg kg^{-1}, respectively.

Non-labile carbon (C_{NL}): The trend for C_{NL} under different cropping systems was the same as for C_T and C_L. Highest value for C_{NL} was under grasses (37.3-39.2 mg kg^{-1}), followed by soybean-wheat (28.04 mg kg^{-1}), maize-wheat (26.41-27.71 mg kg^{-1}) and rice-wheat (14.63-26.13 mg kg^{-1}), with mean values of 38.25, 28.04, 27.06 and 23.13 mg kg^{-1}, respectively.

Lability index (LI): The LI among different cropping systems was highest in grasses (1.08-1.19), followed by soybean-wheat (0.92), rice-wheat (0.69-0.94) and maize-wheat (0.64-0.77), with mean values of 1.14, 0.92, 0.84 and 0.71, respectively.

Carbon pool index (CPI): The CPI was 1.09-1.14 under grasses, 0.96 under soybean-wheat, 0.89 under maize-wheat and 0.71-0.88 under rice-wheat systems, with mean values of 1.12, 0.96, 0.89 and 0.81, respectively.

Carbon management index (CMI): The CMI values were 123.2-129.8 for grasses, followed by 88.0 for soybean-wheat, 52.1-82.5 for rice-wheat and 57.0-69.0 for maize-wheat, with mean values of 126.5, 88.0, 67.6 and 63.0, respectively. Among different cropping systems, only grasses (setaria and guinea grass) had CMI more than 100. Continuous cultivation of any cropping system lowered the CMI below 100.

Table 4.19 Long-term effects of different cropping systems on carbon pools and carbon management index (CMI)

Cropping System	Duration (years)	C_T %	C_L mg kg^{-1}	C_{NL} mg kg^{-1}	LI	CPI	CMI*
Maize-Wheat	32	2.82	1.83	26.41	0.64	0.89	57.0
Maize-Wheat	13	2.99	2.19	27.71	0.77	0.89	69.0
Soybean-Wheat	18	3.02	2.13	28.04	0.92	0.96	88.0
Rice-Wheat	18	2.78	1.69	26.13	0.79	0.88	69.4
Rice-Wheat	14	1.59	1.23	14.63	0.69	0.76	52.1
Rice-Wheat	6	2.86	2.56	26.08	0.94	0.88	82.5
Rice-Wheat	6	2.73	1.59	25.69	0.93	0.71	66.2
Guinea grass	7	4.12	3.89	37.30	1.19	1.09	129.8
Setaria grass	6	4.29	3.72	39.20	1.08	1.14	123.2

* Reference soil was the uncultivated area near the experimental plots

4.6.2 Effect of chemical fertilizers

The data on the effect of long-term use of chemical fertilizers on the carbon pools and carbon management index are presented in Table 4.20.

Total carbon (C_T): The C_T ranged between 1.97% in control and 2.98% in NPK + lime under maize-wheat system; and between 1.44% in control and 1.59% in NPK under rice-wheat system. In maize-wheat system, control had statistically the lowest C_T, followed by N, NP and NPK, and NPK + lime. Improvement in balance among applied nutrients (NPK) improved C_T status of soil.

Labile carbon (C_L): The C_L varied between 1.00 mg kg^{-1} in N and 1.96 mg kg^{-1} in NPK + lime under maize-wheat cropping, and the differences were statistically significant. Rice-

Table 4.20 Long-term effects of chemical fertilizers on different carbon pools and carbon management index (CMI) under maize-wheat and rice-wheat cropping systems

Cropping System	Duration (years)	Treatments	C_T %	C_L mg kg^{-1}	C_{NL} mg kg^{-1}	LI	CPI	CMI*
Maize-Wheat	32	Control[¶]	1.97	1.23	18.51	0.61	0.62	38.3
		100%N	2.36	1.00	22.60	0.41	0.75	30.4
		100%NP	2.71	1.73	25.34	0.63	0.86	53.9
		100%NPK	2.82	1.83	26.41	0.64	0.89	57.0
		100%NPK + lime	2.98	1.96	27.84	0.65	0.94	61.2
LSD (P=0.05)			0.12	0.06	1.23	0.05	0.04	2.1
Rice-Wheat	14	Control[¶]	1.44	0.96	13.41	0.59	0.68	40.4
		100%NPK	1.59	1.23	14.63	0.69	0.76	52.1

*Reference soil was the uncultivated area near the experimental plots

[¶] No fertilizer applied

wheat system had 0.96 and 1.23 mg kg^{-1} labile carbon in control and NPK, respectively.

Non-labile carbon (C_{NL}): Fertilizer applications increased C_{NL} over control. The C_{NL} increased from the lowest value of 18.51 mg kg^{-1} in control to the highest value of 27.84 mg kg^{-1} in NPK + lime plots under maize-wheat system. The C_{NL} in N was significantly higher than control, but lower than in NP and NPK; the later two were statistically at par. Under rice-wheat cropping also C_{NL} increased from 13.41 mg kg^{-1} in control to 14.63 mg kg^{-1} with the application of NPK.

Lability index (LI): The lowest LI in maize-wheat system was observed with N; control, NP, NPK and NPK + lime were statistically at par. Similarly, application of NPK showed higher LI than control under rice-wheat system.

Carbon pool index (CPI): The CPI in maize-wheat system varied between 0.62 in control and 0.94 in NPK + lime. The CPI in NP and NPK was statistically the same, but higher than N, and lower than NPK + lime. Rice-wheat cropping had CPI value of 0.68 in control compared to 0.76 in NPK.

Carbon management index (CMI): Fertilizer application significantly affected CMI in both maize-wheat and rice-wheat systems. Application of N alone for 32 years in maize-wheat system decreased the CMI by about 21% over control. Application of recommended dose of NPK, however, increased CMI by 49% over control. Application of NPK + lime increased CMI by 7% over NPK. Similarly, NPK application to rice-wheat system showed CMI higher than control by about 30%.

4.6.3 Effect of organic amendments

Application of organic amendments (FYM/wheat straw/lantana biomass) increased different carbon pools and CMI under both maize-wheat and rice-wheat systems. The data are presented in Table 4.21.

Total carbon (C_T): Application of organics in combination with NPK increased C_T over

Table 4.21 Effect of continuous application of chemical fertilizers and organics on different carbon pools and carbon management index (CMI) under maize-wheat and rice-wheat cropping systems

Cropping System	Duration (years)	Treatments	C_T %	C_L mg kg^{-1}	C_{NL} mg kg^{-1}	LI	CPI	CMI*
Maize-Wheat	32	100%NPK	2.82	1.83	26.41	0.64	0.89	57.0
		100%NPK + FYM	3.52	3.06	32.13	0.88	1.11	97.7
Maize-Wheat	13	100%NPK	2.99	2.19	27.71	0.77	0.89	69.0
		100%NPK + Lantana	3.52	3.69	31.50	1.14	1.05	120.1
		100%NPK + FYM	3.64	3.42	32.93	1.02	1.09	110.2
Rice-Wheat	18	100%NK	2.78	1.69	26.13	0.79	0.88	69.4
		100%NK + Lantana	3.29	2.76	30.11	1.11	1.04	115.8
Rice-Wheat	14	100%NPK	1.59	1.23	14.63	0.69	0.76	52.1
		50%NPK + FYM	2.01	2.26	17.85	1.04	0.96	99.5
		50%NPK + Wheat straw	1.94	1.69	17.66	0.79	0.92	72.5
Rice-Wheat	6	100%NPK	2.86	2.56	26.08	0.94	0.88	82.5
		100%NPK + Lantana¶	3.30	3.02	29.95	0.97	1.01	97.8
Rice-Wheat	6	100%NPK	2.73	1.59	25.69	0.93	0.71	66.2
		75%N100%PK + 25%N through Lantana	3.02	1.82	28.34	0.97	0.78	75.8

* Reference soil was the uncultivated area near the experimental plots

¶ No-tillage for wheat

recommended NPK alone by about 1.18-1.25 times under maize-wheat and 1.05-1.27 times under rice-wheat system. Application of NPK + FYM to maize-wheat system for 32 years increased the C_T by about 1.25 times over NPK. Application of wheat straw and FYM along with 50% NPK to rice-wheat system for 14 years increased C_T by 1.22 and 1.27 times, respectively, over 100% NPK.

Labile carbon (C_L): Application of FYM along with NPK to maize-wheat system for 32 years increased the C_L by about 67% over NPK. Similarly, application of FYM and lantana along with chemical fertilizers to maize-wheat system for 13 years increased C_L by 1.56 and 1.68 times, respectively, over the recommended NPK. Under rice-wheat system, application of wheat straw and FYM along with 50% NPK for 14 years increased C_L by 1.37 and 1.84 times, respectively, over NPK. Again under rice-wheat cultivation, application of lantana increased C_L by 1.63 times after 18 years, and 1.14-1.18 times after 6 years, over recommended NPK.

Non-labile carbon (C_{NL}): Like C_T, organics increased the C_{NL}. Application of organics increased C_{NL} over the recommended dose of chemical fertilizers alone by about 1.14-1.22 times under maize-wheat and by 1.10-1.22 times under rice-wheat system.

Lability index (LI): Application of FYM along with NPK to maize-wheat system for 32 years increased the LI by about 1.38 times over NPK. Similarly, application of FYM and lantana to maize-wheat system for 13 years increased LI by 1.31 and 1.48 times, respectively, over recommended NPK. Application of wheat straw and FYM along with 50% NPK to rice-wheat system for 14 years increased LI by 1.14 and 1.50 times, respectively, over NPK.

Carbon pool index (CPI): Organic amendments maintained CPI more than one in both maize-wheat and rice-wheat systems. Application of FYM along with NPK to maize-wheat system for 32 years increased the CPI by 1.25 times over NPK. Similarly, application of

FYM and lantana to maize-wheat system for 13 years increased CPI by 1.22 and 1.18 times, respectively, over recommended NPK. Application of wheat straw and FYM along with 50% NPK to rice-wheat system for 14 years increased CPI by 1.22 and 1.27 times, respectively, over NPK. Lantana application in other rice-wheat systems increased CPI by 1.11-1.18 times, over NPK.

Carbon management index (CMI): The CMI with chemical fertilizers only was always lower than 100 in both maize-wheat (57.0-69.0) and rice-wheat systems (52.1-82.5). Application of organics (FYM/wheat straw/lantana biomass) along with chemical fertilizers improved CMI in both maize-wheat and rice-wheat cropping systems. In maize-wheat system, CMI with NPK + organics was either very close to 100 or more than 100 (i.e. 97.7-120.1). In rice-wheat system on the other hand, CMI values, except in one case (115.8), were always lower than 100. Application of organics increased the CMI by 1.60-1.74 times under maize-wheat, and 1.15-1.91 times under rice-wheat system, over NPK.

DISCUSSION

Chapter V

Discussion

The effects of continuous applications of chemical fertilizers, organic manures and liming on soil properties, crop yield and sustainability are discussed in this chapter under the following heads:

- 5.1 Soil chemical and physico-chemical properties
  - 5.1.1 Soil pH
  - 5.1.2 Organic carbon
  - 5.1.3 Available nutrients (N, P and K)
  - 5.1.4 Cation exchange capacity
- 5.2 Soil physical properties
  - 5.2.1 Soil texture
  - 5.2.2 Structural properties
    - 5.2.2.1 Soil aggregation
    - 5.2.2.2 Bulk density, porosity and pore size distribution
    - 5.2.2.3 Air-filled porosity
    - 5.2.2.4 Soil penetration resistance
  - 5.2.3 Hydraulic properties
    - 5.2.3.1 Soil water retention and availability
    - 5.2.3.2 Soil water transmission properties
    - 5.2.3.3 Soil-water contact angle
  - 5.2.4 Mechanical properties
    - 5.2.4.1 Consistency limits
- 5.3 Crop water use
- 5.4 Crop yields
- 5.5 Validation of DSSAT model
- 5.6 Non-limiting water range
- 5.7 Carbon management index

5.1 Soil chemical and physico-chemical properties

5.1.1 Soil pH

The continuous use of chemical fertilizers and FYM for 32 years led to a significant decline in the soil pH from its initial value of 5.8; application of 100% NPK + lime, however, significantly increased the value to 6.5 (Table 4.1) The source of N was urea, which is an acid producing fertilizer (Tisdale *et al.*, 1997). Application of P and K, and FYM had a moderating effect on soil reaction. The moderating effect could be attributed to decrease in the activity of exchangeable Al^{+3} in the soil solution due to chelation effect of organic molecules (Hue, 1992) and formation of aluminophosphate complexes. Lime application along with NPK elevated the soil pH from its initial level of 5.8 to 6.5. These findings are in conformity with a number of workers (Prasad *et al.*, 1996; Sharma *et al.*, 2002).

5.1.2 Organic carbon

After the harvest of wheat (32nd cropping cycle in 2003-04), organic carbon content varied between 7.0 to 12.4 g kg^{-1} (Table 4.1). Zero fertilization and application of N alone through urea decreased the SOC to 7.0-7.2 g kg^{-1} as compared to initial status of 7.9 g kg^{-1}. It could be ascribed to poor root growth and hence, poor biomass addition to the soil (Sharma and Singh, 1991). Application of FYM along with NPK increased the SOC by 57% over its initial status. This substantial build up in the SOC resulted partly due to the addition of FYM, a source of carbon, and partly due to better root growth and addition of more plant residues in this treatment; as was also observed by Kher (1987) and Sharma *et al.* (2002). Slow rate of organic matter decomposition in wet temperate zone of Western Himalayas could be another reason for build up of SOC (Acharya *et al.*, 1988, Sharma *et al.* 2002).

5.1.3 Available NPK

Continuous cultivation for 32 years reduced available N by about 54 to 67% over its initial status of 736 kg ha^{-1} in all the treatments. The leaching losses of N under very high rainfall conditions (2312 ± 618 mm) and its application schedule not synchronizing with the crop requirement might be responsible for mining of these soils with respect to nitrogen. The highest reduction in available N was observed in control plots and lowest in NPK + FYM plots, which was obvious. The reduction in N in control plots resulted due to the removal of N with continuous cropping without fertilization, which caused deficiency and thus reduction in yield (Bhardwaj and Omanwar, 1994). Application of NPK + FYM registered maximum content of available N. It might be due to the additional supply of N through FYM. These results agree with those of Sheeba and Chellamuthu (1999).

Unlike N, the available phosphorus showed a substantial build up with continuous addition of phosphatic fertilizers. The available phosphorus ranged from 5.5 to 135.9 kg ha^{-1}. The highest amount of available P was in NPK + FYM plots. Similar observations were made by Prasad *et al.* (1996) and Sharma *et al.* (2002). The build-up in available P in all the treatments, except control and N, might be attributed to low crop recovery of applied P (Sharma and Gupta, 1994; Zhang *et al.*, 1995). The increase in available P due to FYM may be ascribed to the inactivation of iron and aluminium and hydroxy aluminium ions, which reduces fixation. Also the concentration of P in available pool increased due to extra addition of P through FYM. The increase in available P with the application of lime might be due to reduction in exchangeable acidity and mineralization of organic phosphates (Kumar and Verma, 1997). However, the available P content declined by about 42 and 52% under N and control plots, respectively. The lowest values of available P in control and N probably resulted from its continuous removal without any additions of P in these treatments. In N-treated plots, sharp decline in pH resulted in high P fixation, and thus reduction in available P content.

The exclusion of K in crop nutrition (control, 100% N and 100% NP) led to the mining of native K pools over the years (Prasad *et al.*, 1996; Sharma *et al.*, 2002). Higher levels of K due to FYM application may be ascribed to reduction of K fixation and increase in release of K due to interaction of organic matter with clay, besides the additional K supply in the available K pool of the soil (Mathur, 1997)

5.1.4 Cation exchange capacity

After 32 years of continuous fertilization, the cation exchange capacity increased with the use of NPK, NPK + lime and NPK + FYM, decreased with the use of N alone and remained unaffected under control and NP. The cation exchange capacity of soils is a function of negative charges on the surface of the colloidal particles in soils. The maximum increase in CEC in NPK + FYM could be attributed to the increase in the organic matter content and thus increase in the net negative charge. Liming on the other hand increased the pH, and thus the CEC, due to increase in negative charge on clays, humus and Fe and Al oxides. Use of N alone decreased the pH to 4.4. At such low pH values, only the permanent charges of the clays and a small portion of the charges on the organic colloids hold ions that can be exchanged by cations. At low pH values Al^{3+} and hydroxyl aluminum ions react and bind or block exchange sites in silicate clays and in humus, thereby reducing the CEC of the colloids. If the soil is then limed, these ions are removed, which increases CEC and more base-forming cations can be adsorbed (Brady and Weil, 2002).

5.2 Soil physical properties

5.2.1 Soil texture

Soil texture is a stable soil property. That is why application of chemical fertilizers with or without FYM or lime, except N alone, didn't affect the soil texture. The

N alone through urea changed the texture in favour of finer fraction. This might be due to creation of extremely acidic condition in N alone plots. Under such extreme acid conditions iron becomes soluble and is liberated from the mineral lattice structure, process called ferrolysis. When ions such as Fe^{2+} are removed or are oxidized within the minerals, the rigidity of the mineral structure is weakened and the mechanical breakdown occurs (Brady and Weil, 2002). Migration of clay particles from surface to about 0.08 m depth was observed in all treatments. It might have resulted due to high rainfall events.

5.2.2 Structural properties

5.2.2.1 Soil aggregation

Application of lime, FYM and fertilizers improved the soil aggregation, expressed as mean weight diameter (MWD) and water-stable aggregates (WSA > 0.25 mm dia). The MWD increased with the application of NP, NPK, NPK + FYM and NPK + lime by about 17, 23, 85 and 164%, respectively, over control. However, application of N alone decreased MWD by about 29% over control. Similar trend was observed in case of WSA > 0.25 mm dia. The improvement in aggregation with the addition of NP, NPK, NPK + FYM and NPK + lime is due to the increase in organic carbon content and addition of phosphates. Increase in soil organic carbon content improves soil aggregation by way of forming clay-organic complexes in soil (Greenland, 1965; Bhushan and Sharma, 2002). Addition of phosphates to soil results in the precipitation of Al and Fe as insoluble Al and Fe phosphates, which act as binding agents (Biswas, 1982; Haynes, 1984). Calcium, a constituent of single superphosphate may also take part in mechanism of aggregation (Biswas *et al.*, 1969). Both lime and hydroxyl Al polymers formed by precipitation of exchangeable Al (due to rise in pH) can act as cementing agents, binding soil particles together and improving soil structure (Haynes and Naidu, 1998). The decrease in aggregation due to application of N alone can be attributed to the dispersive action of ammonium ions. Under low pH conditions (unsuitable for nitrification), the ammonium ions may accumulate in soil and like sodium favour dispersion of soil colloids (Aldrich *et al.*, 1945; Fox *et al.*, 1952; Myers and Thein, 1991). Biswas and Ali (1969) also showed adverse effect of nitrogenous fertilizers on soil structure. Although the NH_4^+ content in NP, NPK, NPK + lime and NPK + FYM was higher than N (Appendix-XVIII), the higher contents of P, calcium and/or organic matter masked the adverse effect of NH_4^+ on soil aggregation through their strong cementing effect.

5.2.2.2 Bulk density, porosity and pore size distribution

The bulk density of whole soil (0-0.15 and 0.15-0.30 m soil depths) and soil aggregates (2-8 mm dia) was significantly affected by different treatments. The decrease in bulk density over the control with NP, NPK and NPK + FYM was about 8-14% in 0-0.15 m soil layer, 7-10% in 0.15-0.30 m soil layer and 6-22% in soil aggregates. Bulk density values of soil in N-treated plots were statistically at par with control in both the layers, but increased significantly in soil aggregates. The bulk density in NPK + lime was also at par with control in 0-0.15 m soil layer and in soil aggregates, but was lower in 0.15-0.30 m soil layer. Decrease in bulk density resulted from the dilution of soil matrix (mineral matter) with less dense material (organic matter) and improvement in aggregation, which encourages a fluffy and porous condition in soil and thus a low soil bulk density. The reduction in bulk density of soil due to increase in organic carbon content has been amply reported in literature (Sharma and Aggarwal, 1984; Schjonning *et al.*, 1994; Sharma *et al.*, 1995; Miglierina *et al.*, 2000; Sharma and Bhushan, 2001). Higher bulk density with NPK + lime may be due to cementing effect of $CaCO_3$ precipitation (Acharya *et al.*, 1988). In N-treated plots, the increase in bulk density could be due to the deterioration in soil structure as a result of dispersion caused by accumulation of ammonium ions. Similar results have also been reported in literature where application of N alone increased soil bulk density in comparison to control (Biswas *et al.*, 1971; Bhatnagar *et al.*, 1992; Singh *et al.*, 2002).

Total porosity was computed from bulk density and particle density values. Since particle density was not affected significantly by different treatments, total porosity followed changes in the bulk density of soil. The average values of particle density were 2.56 and 2.57 Mg m^{-3} in 0-0.15 and 0.15-0.30 m soil layer. Since total porosity and bulk density are inversely related, the soil layer that had the lower bulk density, showed the higher porosity and vice-versa. Total porosity increased with the application of NP, NPK and NPK + FYM over control by about 9-15% in 0-0.15 m soil layer, 7-9% in 0.15-0.30 m soil layer and 9-34% in soil aggregates. Application of N alone decreased the total porosity of soil aggregates to 34.2% from 38.5% in control. The NPK + lime, however, increased the total porosity in 0.15-0.30 m soil layer by about 4% over control. Increase in soil porosity with fertilization has also been reported by Yeoh and Oades (1981b), Schjonning *et al.* (1994) and Prasad and Sinha (2000).

The pore-size distribution in 0-0.075 m soil layer was significantly affected by fertilizer applications (Fig. 4.6). This effect may be attributed to the improvement in soil aggregation that leads to creation of secondary coarser pores and the formation of intra-aggregate finer pores (Horn *et al.*, 1994). It results in the increase in water transmission and water storage pore fraction of soil porosity. Miglierina *et al.* (2000) associated increase in water transmission pores in soil to the build-up in soil organic matter and large root system near the soil surface. In the present study applications of NP, NPK and NPK + FYM increased water transmission pores (> 50 μm), decreased residual pores (< 0.5 μm), while did not affect water storage pores (0.5-50 μm). Pore-size distribution in control, N and NPK + lime remained almost the same probably because of small differences in bulk density and total porosity under these treatments. Improvement in soil aggregation due to NPK + lime (Table 4.3) was not reflected into changes in pore-size distribution compared to control due to unknown reasons.

5.2.2.3 Air-filled porosity

The air-filled porosity at any given moisture content was lowest in N-treated, control and NPK + lime plots followed by NP and NPK, and highest in NPK + FYM, in both the layers (Fig. 4.3). The 10% air-filled porosity, considered critical for most of the upland crops, appeared much earlier in NPK + FYM followed by NPK, NP, NPK + lime, control and N (Fig. 4.4). The effect of fertilizer and FYM application on air-filled porosity of soil was manifested through changes in water-transmission pores in soil. The water transmission pores increased with NP, NPK and NPK + FYM by about 32, 34 and 40%, respectively, over control (Fig. 4.6). It helped in attainment of 10% air-filled porosity in the active rooting zone of wheat earlier than N, control and NPK + lime. The 10% air-filled porosity in 0.06-0.09 m soil layer was attained in 5 days in N, control and NPK + lime treatments as against within a few hours in other treatments. The corresponding period in two sets of treatments in 0.15-0.18 m layer was 12-16 and 5-9 days, respectively. Further, the 10% air-filled porosity arrived at a higher moisture content (42.7-45.7%) in NP, NPK and NPK + FYM than in N, control and NPK + lime (38.3-39.2%).

5.2.2.4 Soil penetration resistance

The soil penetration resistance (SPR) is a measure of resistance that must be overcome to cause deformation in soil. In a given soil it depends largely on moisture content and bulk density. The SPR decreases with increase in moisture content and increases with increase in bulk density (Kumar *et al.*, 1971; Kisu, 1978). Increase in bulk density increases the resistance of soil to both, volumetric compression and linear deformation. Any treatment which decreases bulk density is expected to lower SPR. It was clearly demonstrated by the data collected in the present investigation. In both 0.06-0.09 and 0.15-0.18 m soil layers, the SPR was highest in N treated plots, control and NPK +

lime followed by NPK and NP and lowest in NPK + FYM. The sequence followed the order of decrease in bulk density. Reduction in SPR due to decrease in bulk density have also been reported by earlier workers (Ganai and Singh, 1988; Bhagat and Verma, 1991; Sharma and Bhushan, 2001). Various workers have observed reduction in soil penetration resistance with balanced fertilization and organic manures (Obi and Ebo, 1995; Mishra and Sharma, 1997; Prasad and Sinha, 2000; Whitbread *et al.*, 2000).

The SPR was linearly, negatively and significantly correlated with moisture content in all the treatments at both the soil depths (Fig. 4.7 and equations. 4.1-4.12). The SPR decreased with the moisture content because increase in moisture content decreases the inter-particle binding and the soil can be easily deformed. The reduction in SPR with increase in moisture content is well documented in literature (Bateman *et al.*, 1965; Gu and Wen, 1981; Larson and Clapp, 1984; Tester, 1990; Sharma and Bhushan, 2001).

5.2.3 Hydraulic properties

5.2.3.1 Soil water retention and availability

Soil water retention (mass basis) was lowest in N-treated plots and highest in NPK + FYM at all suction values; other treatments were in the intermediate range. When expressed on volume basis, the effect of various treatments narrowed upto 10 kPa suction and reversed at higher suctions. The NPK + FYM had the lowest water retention at -1500 kPa.

The differences among different treatments were primarily due to differences in organic carbon and structure. It could be explained due to the reason that the water retention of soils depends primarily on (i) the number and size-distribution of soil pores and (ii) the specific surface area of soils. Soil structure and pore-size distribution affect water retention mainly at lower suction values (0-100 kPa), while water retention at higher suction values is influenced more by specific surface area of soil constituents (Hillel, 1980).

The organic matter affects both these soil properties. It increases soil pores favourable for water retention and specific surface area of soils. The water holding capacity of organic matter is very high. Lowest bulk density, highest total porosity and highest soil organic carbon content in NPK + FYM caused highest water retention between saturation and 1500 kPa suction. Reverse was true for control and N treatments. Other treatments showed intermediate effects. The effects on volume wetness were not as dramatic as on mass wetness (Table 4.6). It happened due to the fact that increase in mass wetness primarily due to SOC build-up was counter-balanced by decrease in soil bulk density.

The plant available water capacity (PAWC) was higher with all the treatments, except N, than control on both mass and volume basis. The PAWC was lowest with N and highest with NPK + FYM (Table 4.6). Further, differences in PAWC due to different treatments were more pronounced when expressed as mass wetness, but narrowed down when expressed as volume wetness due to reasons explained earlier. Similar observations were made by Bhushan and Sharma (2005). Increase in water retention and PAWC with balanced fertilization and application of manures have also been reported by many workers (Acharya *et al.*, 1988; Bhatnagar *et al.*, 1992; Prasad and Sinha, 2000; Whitbread *et al.*, 2000; Amgain and Singh, 2001).

5.2.3.2 Soil water transmission properties

Water transmission through soil is closely related to the pore-size distribution. Infiltration, saturated hydraulic conductivity and water subsidence rate in the plots increased with the increase in water transmission pores of soil in different treatments (Table 4.8) Lowest values of water transmission were observed in N, control and NPK + lime followed by NP and NPK, and highest in NPK + FYM. Application of NPK + lime, NP, NPK and NPK + FYM increased steady-state infiltration rate by about 4, 50, 56 and 104%, saturated hydraulic conductivity by 52, 117, 143 and 305% and water subsidence rate by

30, 90, 100 and 370%, respectively, over control.

Layer-wise percolation studies indicated that water percolation was highest in 0.05 m soil layer under all the treatments, and that water permeability decreased with soil depth. The highest water permeability in surface 0-0.05 m layer may possibly be associated with relatively loose soil structure, higher organic matter and higher sand content. The least water permeability of 0.15-0.20 m soil layer may be associated with sub-soil compaction. The tillage depth is usually upto 0.12 m; the soil below remains undisturbed and may eventually get compacted. Application of $CaCO_3$ results in clogging through its accumulation on the internal surfaces of pores (Greene *et al.*, 1978; Al-Ani and Dudas, 1988) resulting in reduced water permeability.

Improvement in soil-water transmission properties with the addition of phosphates and/or balanced fertilizers with or without FYM or lime have been well documented in literature (Pillsbury, 1947; Bhatia and Shukla, 1982; Acharya *et al.*, 1988; Chawla and Chabra, 1991; Obi and Ebo, 1995; Grewal *et al.*, 1999; Prasad and Sinha, 2000; Barzegar *et al.*, 2000; Tiwari *et al.*, 2000).

5.2.3.3 Soil-water contact angle

Application of chemical fertilizers increased the soil-water contact angle; the effect being more pronounced with the application of NPK + FYM. The soil-water contact angle increased with the increase in soil organic carbon content, making soil less hydrophyllic as was also observed by Das and Das (1972), Kumar *et al.* (1984) and Bhushan (1998). Application of lime on the other hand resisted the change in soil-water contact angle. It could be due to higher number of cations which might attract water and thus lower the soil-water contact angle.

5.2.4 Mechanical properties

5.2.4.1 Consistency limits

Soil consistency limits determine the workability of soils. The best moisture range for tillage is between plastic limit and shrinkage limit of soil. In this range the soil is friable. The plasticity index, which is the difference between liquid limit and plastic limit, indicates the moisture range through which soil has properties of plastic material. Utomo and Dexter (1981) observed that for some soils gravimetric moisture content around 0.9 times the plastic limit provided the maximum friability. At this moisture content, soil tillage maximizes the proportion of small aggregates (Ojeniyi and Dexter, 1979).

All treatments increased liquid limit, plastic limit, shrinkage limit and plasticity index significantly over the control; the highest values were observed in NPK + FYM (Table 4.10). Consistency limits have been reported to be positively correlated with organic matter, clay content and cation exchange capacity (Canbolat *et al.*, 1999). Increase in consistency limits might be due to increase in organic matter in NP, NPK, NPK + lime and NPK + FYM, and due to increase in clay content in N alone treatment. The increase particularly in plastic limit moisture content occurs because hydration of organic matter must be fairly complete before sufficient water is available for the film formed around the mineral particles, thereby making the soil plastic. According to Atterberg limits (1913), as quoted by Jumikis (1967), all the soils were in the medium plastic range.

Friability range was highest in control and N (9.1-9.6%), followed by NP and NPK (8.5-8.6%), and lowest in NPK + lime and NPK + FYM (7.9-8.2%). Friability range decreased with application of chemical fertilizers with or without FYM or lime in comparison to control. However, these soils became friable at higher moisture content than control, because of increase in plastic limit.

5.3 Crop water use

Profile water use and total water use (profile water use + irrigation + rainfall) were determined between different phenological phases of wheat (2003-04 and 2004-05) in 0-0.90 m soil depth (Fig 4.11 and 4.12).

Profile water use by wheat crop was lowest under N and highest under NPK + FYM treatments. Profile water use increased with the improvement in the balance of NPK applied through chemical fertilizers, and increased further by application of FYM or lime. It might be due to improvement in both root and shoot growth, as evidenced by biomass production (Tables 4.11 and 4.12), as a result of better physical and chemical environment with application of balanced fertilization and FYM/lime. Profile water use in NP was similar to that in NPK. Similarly, profile water use by wheat crop in NPK + lime and NPK + FYM was almost equal.

Total water use by wheat under different treatments followed the trend as in profile water use, during both the years. The very high values of total water use recorded at tillering-flowering were due to high rainfall during this period (282.5 mm during 2003-04 and 515.3 mm during 2004-05) which was included in the computation of total water use. Otherwise also, water requirement of a crop is the maximum during the vegetative phase.

5.4 Crop yields

The effect of continuous application of fertilizers, FYM and lime was similar on yield of both maize and wheat (Tables 4.11 and 4.12) and thus the system productivity (Table 4.13). The omission of chemical fertilizers and amendments (in control) for the last thirty-two years to maize-wheat cropping system resulted in considerably low yields of both the crops due to continuous mining of the nutrients and unfavorable soil physical conditions. Application of N alone continuously for thirty-two years resulted in zero yields. These plots were rendered completely unsuitable for crop growth. Earlier reports have shown degradation of soils in plots treated with nitrogen through nitrogenous fertilizers alone and thereby resulting in zero yield levels after about twenty to thirty years of experimentation (Sinha *et al.*, 1997; Santhy *et al.*, 1998; Swarup, 2000 and Sharma *et al.*, 2002). It may be due to increase in soil acidity resulting in increased concentration of various toxic elements especially Al, which adversely affect crop growth (Mengel and Kirkby, 1987). These plots had the worst physical environment among different treatments.

The NP application improved the yield in comparison to control. Application of P improved the physical properties of the soil in comparison to control and N. It also decreased soil acidity (and Al toxicity) and increased exchangeable cations, thus influencing crop yield (Verma and Singh, 1996). Similar increases in crop yields due to P additions over N only treatment have been reported by various workers (Prasad *et al.*, 1996; Santhy *et al.*, 1998 and Sharma *et al.*, 2002).

The balanced application of NPK further improved the soil properties (physical and chemical) and sustained the yields of both the crops over NP. The balanced application of N, P and K significantly increased the yield over NP treatment. Prasad *et al.* (1996) and Sharma *et al.* (2002) also reported similar increases in yield due to balanced application of NPK, which were attributed to improvement in soil fertility. The much lower yield in NP was due to deficiency of K. Deficiency in K results in low photosynthetic efficiency, impaired aeration and various physiological disorders in crop plants (Rao and Khera, 1995).

The highest levels of yields were obtained in the treatments where the amendments like FYM and lime were added along with NPK as a result of improvement in both physical and chemical soil properties. The reasons for increased response to FYM are generally ascribed to the beneficial effects of FYM on soil productivity (Brady and Weil, 2002). Application of lime, on the other hand, increased the soil pH and decreased the active forms of Al and soil acidity, which resulted in higher crop yields (Sumner *et al.*, 1986).

5.5 Validation of DSSAT model

The "Decision Support System for Agrotechnology Transfer" (DSSAT) model was tested for the estimation of crop yields and soil moisture contents under different treatments in the long-term fertilizer experiment. The model estimated the grain yields close to the observed values in NPK + FYM and NPK + lime, and over-estimated in all other treatments. Nevertheless, the trend for simulated yields under various treatments was similar to the observed ones, except in N. The actual crop yield is influenced by a combination of various chemical, physical and biological factors, while DSSAT model considered mainly the N status, neglecting the effect of other macro and micro-nutrients, while simulating the crop yields. The pH in N plots had significantly declined to a value of 4.4 and at the same time the soil was depleted of phosphorus, potassium and secondary and micronutrients, resulting into zero biomass production. The DSSAT model on the other hand based on 100% N application rate simulated a yield of 3.43 Mg ha^{-1}. Probably the values of soil pH and other nutrient levels (except N) in N plots were beyond the limits of DSSAT model, which resulted in such a large difference in observed and estimated values of wheat grain yield. The crop in NP plots showed a severe deficiency of potassium, thus causing a significant decline in the yield over the NPK treatment. However, the yields estimated under NP and NPK were almost similar. The close estimation under NPK + lime and NPK + FYM are because of the optimum conditions under these plots.

The model underestimated the moisture content in the surface layer (0-0.05 m) at all the phenologoical stages of wheat than the observed values, indicating the highest moisture loss at soil surface. The deviations of estimated soil moisture contents from the observed data were higher in the upper soil layers. The root mean square error (RMSE), which denotes the theoretical standard deviation between observed and expected sample means, was maximum in the surface layers and lower for deeper layers. The under-estimation of moisture content could be due to over-estimation of water losses through evapotranspiration. Eitzinger *et al.* (2004) reported that the DSSAT simulated evapotranspiration values were significantly higher than the measured ones, which could be due to deviations in the calculations of the front root velocity and soil water extraction as well as potential evapotranspiration. The model also over-estimated the moisture content during the final stages in the cropping season, which might be due to the under-estimation of the water flux towards upper layers.

Ines *et al.* (2001) concluded that DSSAT has more empiricism in simulating the soil water balance and is therefore not generally applicable when soil moisture is an important parameter. The soil water balance module (SWBM) of DSSAT v 3.5 showed a low performance to simulate soil moisture profiles. The SWBM simulated high water extraction from surface layers due to high root density estimation by the growth module. Faria and Bowen (2003) attributed it to the inadequacies in the methods used to calculate soil water flux and root water absorption. According to the module, the surface soil layer supplied all the water for evaporation. It under-estimated the upward water flux required to replace extracted water. It also under-estimated the drainage in unsaturated conditions in deeper layers and the simulated moisture content was close to the field capacity, differing from the observed values.

5.6 Non-limiting water range

The non-limiting water range (NLWR) represents the soil moisture range between two limits for plant growth– the aeration limit as the upper limit and the mechanical resistance critical for root growth as the lower limit (Letey, 1985). The upper limit of NLWR could be the critical oxygen diffusion rate (ODR), 10% air filled porosity or moisture content at -10 kPa potential (Letey, 1985; da Silva *et al.*, 1994; Topp *et al.*, 1994; Carter *et al.*, 1999; Sharma and Bhushan, 2001). The lower limit is the mechanical resistance at which the root growth is reduced to about half. This value varies with soil and crop. For wheat in medium textured soils, the critical mechanical impedance may be around 1.75-2.00 MPa (Taylor *et al.,* 1966; Carter *et al.,* 1999; Sharma and Bhushan, 2001). It has been observed that the soil management practices, which result in an increased NLWR, can maximize the potential of a soil for crop production (da Silva and Kay, 1997b; Sharma and Bhushan, 2001; Benjamin *et al.,* 2003).

In the present study, 10% air-filled porosity was used as the upper limit and 2 MPa SPR as the lower limit for NLWR. Among different cropping systems, NLWR was highest in soybean-wheat (16.8%), followed by grasses (14.4-15.6%) and maize-wheat (13.1-15.4%), and lowest in rice-wheat (7.5-11.0%). It might be due to very high biomass additions in soybean-wheat and due to deterioration in structure by puddling in rice-wheat system.

Under maize-wheat system continuously fertilized for 32 years, the NLWR was highest in NPK + FYM, followed by NPK, NP, NPK + lime, control and N alone. The N treated plots had NLWR significantly lower than control. The NLWR improved due to improvement in physical properties especially soil structure and bulk density as a result of increase in the organic carbon content of soil. Application of N alone resulted in lowest NLWR due to the deleterious effect of nitrogenous fertilizer on soil structure, which increased the bulk density and clay content of soil. The NLWR has been observed to be negatively related with clay and bulk density, and positively with organic carbon content of soil (daSilva and Kay, 1997a).

The NLWR was linearly, significantly and positively correlated with grain yield (r = 0.646** during 2003-04 and r = 0.706** during 2004-05). The NLWR considers only the physical properties. In the present study, however, chemical properties also varied significantly under different treatments. The correlation coefficient, otherwise, would have been still higher. In N-treated plots the grain yield was zero. In these plots the extremely acidic conditions (pH = 4.4) resulted in aluminum toxicity and therefore the effect of chemical fertility dominated over the physical fertility on grain yield. In NPK + lime the yields were comparable to NPK + FYM even though the NLWR was narrow. This might be due to improvement in soil chemical conditions and higher nutrient availability due to rise in pH (6.5). Moreover the moisture content during the important phases in cropping season was well above the critical SPR (2 MPa SPR).

Application of organics increased the NLWR in both maize-wheat and rice-wheat systems. Improvement in physical conditions increased the moisture content at 10% air-filled porosity and decreased the moisture content corresponding to 2 MPa SPR, and thus increased the NLWR.

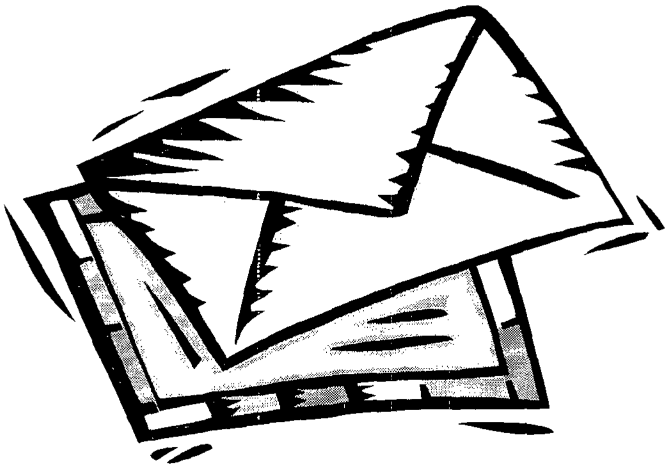
5.7 Carbon management index

Carbon management index (CMI) is a measure of sustainability of soil health. It indicates whether a system is in decline or being rehabilitated. It takes into account both labile and non-labile pools of carbon, which results in a more definitive picture of soil carbon. For a system to be sustainable, the CMI should be more than or equal to 100 (Blair *et al.*, 1995). The effect of chemical fertilizers and organic amendments on CMI under different cropping systems was studied during the present investigation.

Among different cropping systems, the total carbon, labile carbon, non-labile carbon, lability index, carbon pool index and carbon management index were highest under grasses, followed by soybean-wheat and maize/rice-wheat system. The highest values under grasses probably resulted due to the fact that the system remained un-tilled and large amounts of shoot and root biomass accumulated in the surface layer resulting in an increase in various pools of carbon. Cultivation has been shown to decrease the organic carbon content of soils (Dalal and Mayer, 1986; Whitbread *et al.*, 1998; Blair, 2000). That is why the various pools of carbon and CMI were lower in tilled systems viz., soybean-wheat, maize-wheat and rice-wheat. Reduction in labile carbon due to cropping is proportionately greater than the decline in non-labile carbon (Blair *et al.*, 1995). Among these systems, soybean crop left larger amount of crop residues resulting in higher soil carbon contents and thus higher CMI. The sustainability of various systems was in the order: grasses > soybean-wheat > maize/rice-wheat. Among different cropping systems only grasses had CMI > 100.

Application of chemical fertilizers increased the labile and non-labile carbon and thus CMI in comparison to control in both maize-wheat and rice-wheat systems. The improvement was more when chemical fertilizers were applied in balanced form. Balanced use of NPK enhanced the SOC restoration probably due to higher root biomass and rhizodeposition even under intensive cultivation. No fertilization or imbalanced fertilization, on the other hand, leads to negative impact on SOC restoration. Similar observations were made by Singh *et al.* (2003). The application of chemical fertilizers thus improved the carbon pools and increased CMI, making the system more sustainable.

Irrespective of the cropping system, application of organic amendments along with chemical fertilizers further increased the carbon pools and CMI. Organics helped in maintaining or even improving the system sustainability comparable to uncultivated reference soil. Integrated use of NPK fertilizers along with manures further enhances this effect on SOC restoration (Singh *et al.*, 2003). Addition of organic matter to the soil in the form of crop residues and organic amendments increases the level of macro-organic matter (Carter *et al.*, 1998; Kay, 1998), which is important for soil functioning and thus sustainability. Therefore, to improve and maintain carbon pools and their activities, and thus sustain the system, a regular addition of organic materials to soil is crucial.



SUMMARY

Chapter VI

Summary

A field experiment was initiated in 1972-73 in a medium textured, acid Alfisol to investigate long-term effects of chemical fertilizers alone or in combination with soil amendments (FYM and lime) on soil and crop yields under maize (*Zea mays*)- wheat (*Triticum aestivum* L) cropping system. The present study was undertaken to physically characterize the soil after 32 years of imposition of different fertilizer and amendment treatments. Physical characterization of soil using 'non-limiting water range' and evaluation of soil for sustainability using 'carbon management index' was also carried out under different cropping systems viz., maize-wheat, rice-wheat, soybean-wheat and grasses. The DSSAT model was also evaluated for soil-water balance under wheat crop.

The experiment was established in *rabi*, 1972-73 with ten treatments comprising different combinations of NPK, lime, zinc and FYM. The eleventh treatment, consisting of 100 per cent NPK (-S) was introduced in *kharif*, 1981. However, for the present study (during 2003-04 and 2004-05) six treatments viz., Control, N, NP, NPK, NPK + FYM and NPK + lime were selected. The experiment was laid in randomized complete block design with four replications and plot size of 15 m^2 (5m x 3m). The experimental soil was silt loam in texture, acidic in reaction, and medium in NPK and organic carbon. The NPK corresponded to 120 N-60 P_2O_5-40 K_2O kg ha^{-1} for maize, and 120 N-60 P_2O_5-30 K_2O kg ha^{-1} for wheat. The sources of N, P and K were urea, single superphosphate and muriate of potash, respectively. The FYM was applied at the rate of 10 t ha^{-1} on fresh weight basis in NPK + FYM, and lime at 900 kg ha^{-1} as marketable lime ($CaCO_3$) in NPK + lime to maize crop only. Maize (KH-101) was sown on 16th June in 2003 and 8th June in 2004, and wheat on 6th November in 2003 (PBW-343) and 25th November in 2004 (HS-240).

Some treatments comprising chemical fertilizers with or without organics in different on-going long-term experiments under different cropping systems, viz. maize-wheat, rice-wheat, soybean-wheat and grasses (Guinea grass and Setaria) at the university farm, were selected for the determination of 'non-limiting water range' (NLWR) and 'carbon management index' (CMI).

The continuous application of chemical fertilizers and amendments significantly affected the soil chemical, physical and physico-chemical properties determined after the harvest of wheat (2003-04) in the 0-0.15 m soil layer. The soil pH decreased significantly in all the treatments, except NPK + lime. The pH decreased from the initial value of 5.8 to 5.6 in control, 5.1-5.2 in NP, NPK and NPK + FYM, and 4.4 in N; it increased to 6.5 in NPK + lime. The soil organic carbon (SOC) content decreased from initial value of 7.9 g kg^{-1} to 7.0 g kg^{-1} in control and 7.2 g kg^{-1} in N; it remained almost the same in NP and NPK (each 8.0 g kg^{-1}), but increased in NPK + lime and NPK + FYM to 8.4 and 12.4 g kg^{-1}, respectively. Available N and K showed a significant decline, while P increased significantly in all treatments (except in treatments without P) compared to their initial status. The available N, P and K were lowest in control and highest in NPK + FYM. The corresponding values were 243.0 and 335.2 kg ha^{-1} for N, 5.5 and 135.9 kg ha^{-1} for P, and 122.4 and 223.1 kg ha^{-1} for K. The cation exchange capacity was lowest in N, followed by control, NP, NPK and NPK + lime, and highest in NPK + FYM. The respective values were 10.84, 11.48, 13.14, 14.72, 15.22 and 16.06 c mol (p$^+$) kg^{-1}.

Soil texture remained unaffected under all treatments, except in N. The N alone through urea changed the texture in favour of finer fraction. The clay content at different depths upto 0.30 m increased by 0.7-2.9% in N treatment as compared to other treatments. The N treatment had statistically the highest clay and lowest sand content in 0-0.15 m soil layer; silt content was the same under all treatments. In 0.15-0.30 m soil layer, all the three soil fractions were statistically the same under all the treatments.

The soil structural properties, characterized by soil aggregation, bulk density, total porosity, air-filled porosity, pore-size distribution and soil penetration resistance, were significantly affected by different treatments. The MWD increased with the application of NP, NPK, NPK + FYM and NPK + lime by about 17, 23, 85 and 164%, respectively, over control; N alone decreased MWD by about 29% over control. Similar trend was observed in case of WSA > 0.25 mm dia. The WSA varied between 62.9% in N and 89.6% in NPK + lime. The bulk density of soil and soil aggregates (2-8 mm) was highest in N and lowest in NPK + FYM. The corresponding values were 1.35 and 1.15 Mg m^{-3} for 0-0.15 m, 1.35 and 1.22 Mg m^{-3} for 0.15-0.30 m soil depth, and 1.69 and 1.24 Mg m^{-3} for soil aggregates. The decrease in bulk density with NP, NPK and NPK + FYM was about 8 -14% in 0-0.15 m soil layer, 7-10% in 0.15-0.30 m soil layer and 6-22% in soil aggregates. Bulk density values in N-treated plots were statistically at par with control in both the layers, but significantly higher in soil aggregates. The particle density remained unaffected by different treatments with an average value of 2.56 and 2.57 Mg m^{-3} in 0-0.15 m and 0.15-0.30 m soil layers. Therefore, total porosity followed the same trend as the bulk density of soil. Total porosity increased with the application of NP, NPK and NPK + FYM over control by about 9-15% in 0-0.15 m soil layer, 7-9% in 0.15-0.30 m soil layer and 9-34% in soil aggregates. Application of N alone decreased the total porosity of soil aggregates by about 21% over control. The air-filled porosity at any given moisture content was lowest in N, control and NPK + lime followed by NP and NPK, and highest in NPK + FYM. The 10% air-filled porosity (critical value for most of the upland crops) in 0.06-0.09 m soil layer was attained within a few hours in NPK + FYM, NPK and NP, and in 5 days in NPK + lime, control and N. In 0.15-0.18 m soil layer, it appeared much earlier in NPK + FYM (5 days) followed by NPK, NP, NPK + lime, control and N (9-16 days). The water transmission pores (> 50 μm) increased, residual pores (< 0.5 μm) decreased, and the water storage pores (0.5-50 μm) remained almost the same with decrease in bulk density and improvement in soil structure due to applications of NP, NPK and NPK + FYM, in comparison to N, control and NPK + lime. The SPR in general decreased with the increase in moisture content and decrease in bulk density. It was highest in N, control and NPK + lime followed by NPK and NP, and lowest in NPK + FYM.

The soil hydraulic properties like soil water retention, plant available water capacity (PAWC), infiltrability, saturated hydraulic conductivity, water subsidence rate, *in-situ* layer-wise water percolation and soil-water contact angle were also significantly affected by different treatments. Soil water retention (on mass basis) was lowest in N and highest in NPK + FYM plots at all suction values (0, 10 and 1500 kPa); other treatments showed intermediate values. When expressed on volume basis, the effect of various treatments on water retention narrowed upto 10 kPa suction and reversed at higher suctions. The NPK + FYM had the lowest water retention at -1500 kPa. The PAWC on both mass and volume basis was higher with all the treatments, except N, than control. The PAWC was lowest with N and highest with NPK + FYM. The differences in PAWC under different treatments were of lower magnitude when expressed on volume than on mass basis. Infiltration rate, saturated hydraulic conductivity and water subsidence rate were lowest in N, control and NPK + lime followed by NP and NPK, and highest in NPK + FYM. Application of NPK + lime, NP, NPK and NPK + FYM increased final infiltration rate by about 4, 50, 56 and 104%, saturated hydraulic conductivity by 52, 117, 143 and 305%, and water subsidence rate by 30, 90, 100 and 370%, respectively, over control. The percolation rate in the surface 0.10 m layer was highest in NPK + FYM, followed by NPK, NP, control, N and NPK + lime. The least permeable layer within 0-0.25 m depth was 0.15-

0.20 m in N, NP, NPK and NPK + FYM, and 0.10-0.15 m in control and NPK + lime. The soil-water contact angle increased with the increase in soil organic carbon content. Application of lime on the other hand resisted change in soil-water contact angle. The values of soil-water contact angle under different treatments varied between 58.57^0 in control and 63.65^0 in NPK + FYM.

The soil consistency limits, viz. liquid limit, plastic limit, shrinkage limit and plasticity index were highest in NPK + FYM and lowest in control; N, NP, NPK and NPK + lime being intermediate. Liquid limit and plastic limit in N was at par with NPK + FYM. All the soils were in the medium plastic range. Friability range was highest in control and N (9.1-9.6%), followed by NP and NPK (8.5-8.6%), and lowest in NPK + lime and NPK + FYM (7.9-8.2%). Although, the friability range compared to control, decreased with the application of chemical fertilizers with or without FYM or lime, the soils became friable at relatively higher moisture contents.

The profile-water use in wheat at all phenological stages during both the years was minimum in N and maximum in NPK + FYM. It varied from 8.4 to 15.6 mm during sowing-tillering, -20.0 to 1.5 mm during tillering-flowering, 58.7 to 110.0 mm during flowering-physiological maturity, 26.4 to 54.8 mm during physiological maturity-harvest, and 73.5 to 181.9 mm during sowing-harvest in 2003-04. The corresponding values during 2004-05 were 2.8 to 11.2, 3.0 to 14.9, -8.5 to 6.7, 61.4 to 108.0 and 58.8 to 140.9 mm, respectively. During both the years, various treatments for profile-water use numerically followed the order: NPK + FYM > NPK + lime > NPK > NP > control > N. The rainfall and irrigation remaining the same for all the treatments, the total water use (profile-water use + rainfall + irrigation) in wheat followed the similar trend.

Various treatments significantly affected the maize and wheat yield, and system productivity. The N plots did not produce any biomass during both the years. Among other treatments, control produced significantly the lowest and NPK + FYM the highest biomass (grain and straw yields). Maize grain yields were 0.47-4.27 Mg ha^{-1} during 2003 and 0.58-6.03 Mg ha^{-1} during 2004; maize stover yields were 1.14-10.39 Mg ha^{-1} during 2003 and 1.34-10.17 Mg ha^{-1} during 2004; wheat grain yields were 0.35-2.33 Mg ha^{-1} during 2003-04 and 0.59-3.33 Mg ha^{-1} during 2004-05; wheat straw yields were 0.63-5.38 Mg ha^{-1} during 2003-04 and 1.75-7.91 Mg ha^{-1} during 2004-05. The respective increase in yield over control with NP, NPK, NPK + lime and NPK + FYM was 1.49, 2.09, 3.58 and 3.80 Mg ha^{-1} during 2003, and 2.45, 3.81, 4.72 and 5.45 Mg ha^{-1} during 2004 for maize grain; 3.82, 5.24, 8.63 and 9.25 Mg ha^{-1} during 2003, and 2.91, 5.84, 6.63 and 8.83 Mg ha^{-1} during 2004 for maize stover; 0.75,1.39, 1.97 and 1.98 Mg ha^{-1} during 2003-04, and 1.71, 2.12, 2.52 and 2.74 Mg ha^{-1} during 2004-05 for wheat grain; 2.59, 3.93, 4.60 and 4.75 Mg ha^{-1} during 2003-04, and 3.42, 4.26, 5.13 and 6.16 Mg ha^{-1} during 2004-05 for wheat straw. Except in N (zero yields), the system productivity was lowest in control and highest in NPK + FYM; the corresponding values were 0.82 and 6.59 Mg ha^{-1} during 2003-04, and 1.17 and 9.36 Mg ha^{-1} during 2004-05. The elimination of K from plant nutrition (i.e. NP) caused a decline in system productivity over NPK by 1.24 and 1.78 Mg ha^{-1} during 2003-04 and 2004-05, respectively.

The "Decision Support System for Agrotechnology Transfer" (DSSAT) model was tested for the prediction of wheat yields and soil moisture contents under different treatments. The model predicted the grain yields close to the observed values in NPK + FYM and NPK + lime, and over-predicted in all other treatments. Nevertheless, the trend in simulated wheat yield under different treatments was the same as in observed yields, except in N. The soil-water balance module of the DSSAT v 3.5 underestimated the moisture content in the surface layer (0-0.05 m) at all the phenologoical stages of wheat compared to observed values, indicating the highest moisture loss at soil surface. The deviations in simulated data from the observed data were higher in the upper layers as indicated by the root mean square error (RMSE) values. The model under-estimated the moisture contents in 0-0.90 m depth upto physiological maturity, and over-estimated between physiological maturity and crop harvest.

The non-limiting water range (NLWR) was highest in soybean-wheat (16.8%), followed by grasses (14.4-15.6%) and maize-wheat (13.1-15.4%), and lowest in rice-wheat (7.5-11.0%). Under maize-wheat system continuously fertilized for 32 years, the NLWR was highest in NPK (13.1%), followed by NP (12.2%), NPK + lime (9.4%) and control (9.0%), and lowest in N (7.7%). Application of organics increased the NLWR in both maize-wheat and rice-wheat systems. Higher the NLWR, better is the soil physical condition for crop growth. The NLWR was linearly, significantly and positively correlated with grain yield ($r = 0.646^{**}$ during 2003-04 and $r = 0.706^{**}$ during 2004-05). The NLWR:PAWC ratio, which indicate deviation from the classical concept of water availability to plants, also improved with fertilization, except in N; organics further improved the ratio. Higher the ratio, better is the soil physical condition.

Carbon management index (CMI) is a measure of sustainability of soil health. For a sustainable system, $\text{CMI} \geq 100$. Among different cropping systems, the total carbon, labile carbon, non-labile carbon, lability index, carbon pool index and carbon management index were highest under grasses, followed by soybean-wheat and maize/rice-wheat system. The various carbon pools and CMI were lower in tilled i.e. soybean-wheat, maize-wheat and rice-wheat than in untilled systems i.e. grasses. Among different cropping systems only grasses had $\text{CMI} > 100$. Balanced application of chemical fertilizers increased the labile and non-labile carbon and thus CMI in both maize-wheat and rice-wheat systems, in comparison to control. Irrespective of the cropping system, application of organic amendments along with chemical fertilizers increased the carbon pools and CMI, in comparison to chemical fertilizers alone and thus maintained or even improved the system sustainability in comparison to uncultivated reference soil.

Conclusions

1. Balanced use of chemical fertilizers improved soil physical properties compared to control, while N alone through urea showed an adverse effect. Integration of organics with chemical fertilizers further enhanced the beneficial effect, while liming along with NPK had an intermediate effect on soil physical properties.
2. The 'non-limiting water range', a single value soil physical index, improved with the balanced use of chemical fertilizers; the effect enhanced further when organics were applied with chemical fertilizers. The index showed significant and positive correlation with wheat grain yield.
3. As per the 'non-limiting water range', soybean-wheat had better soil physical conditions, followed by grasses, maize-wheat and rice-wheat cropping systems.
4. Application of chemical fertilizers in balanced form enhanced the 'carbon management index' indicating an improvement in sustainability of the production system; maximum improvement was observed when organics were applied along with chemical fertilizers.
5. As per the 'carbon management index' grasses were the most sustainable production system, followed by soybean-wheat and maize/rice-wheat systems.
6. The DSSAT v 3.5 crop model was not found suitable for predicting crop yields as well as profile water status in long-term fertilizer experiments, as it is based mainly on N status, ignoring the effects of variations in other macro and micro-nutrients in soil.

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APPENDICES

Appendix-I

Mean monthly air temperature and rainfall of Palampur (HP) for the period 1974-2004

Month	T_{Min}	T_{Max}	Rainfall	Evaporation
January	5.0 ± 0.9	15.1 ± 1.4	94.7 ± 73.4	53.6 ± 10.7
February	6.4 ± 1.2	16.4 ± 1.9	98.5 ± 63.0	64.0 ± 14.4
March	9.9 ± 1.6	20.3 ± 2.4	106.1 ± 79.2	109.9 ± 28.5
April	14.7 ± 1.7	25.8 ± 1.9	57.8 ± 45.6	161.6 ± 27.4
May	18.2 ± 1.4	29.4 ± 2.1	77.7 ± 62.9	216.8 ± 55.4
June	19.7 ± 0.9	29.9 ± 1.3	219.1 ± 128.8	178.1 ± 40.9
July	19.8 ± 0.5	26.7 ± 1.1	660.9 ± 327.0	95.3 ± 34.5
August	19.4 ± 0.4	26.1 ± 0.7	666.4 ± 159.3	78.8 ± 21.4
September	17.8 ± 1.1	26.0 ± 0.8	228.3 ± 128.0	90.0 ± 18.0
October	13.6 ± 0.8	24.7 ± 1.1	28.7 ± 41.7	103.5 ± 19.6
November	9.7 ± 0.8	21.3 ± 1.6	19.9 ± 28.5	78.9 ± 10.1
December	6.5 ± 0.6	17.2 ± 1.6	54.3 ± 61.5	59.2 ± 11.3

Appendix-II

Mean weekly meteorological data for the period of experimentation during 2003-04

Standard week	Week interval	Temperature (°C)		Rainfall (mm)	Evaporation (mm)	Bright sun-shine hours
		Max.	Min.			
24	11-17 Jun	33.1	19.8	24	57.4	6.9
25	18-24	30.7	18.6	25	37.1	6.9
26	25-1 Jul	29.5	19.6	26	33.1	6.7
27	2-8	27.9	19.6	27	29.8	7.1
28	9-15	27.5	18.5	28	24.1	6.0
29	16-22	26.5	19.5	29	23.3	2.1
30	23-29	28.4	20.7	30	24.2	5.0
31	30-5 Aug	26.9	20.4	31	21.5	2.4
32	6-12	28.0	18.6	32	26.6	5.4
33	13-19	28.3	17.5	33	25.8	5.6
34	20-26	27.5	19.8	34	20.2	4.6
35	27-2Sep	27.5	19.5	35	21.5	4.5
36	3-9	26.5	18.3	36	17.8	4.7
37	10-16	27.4	18.6	37	21.1	3.7
38	17-23	27.4	18.6	38	22	5.6
39	24-30	25.9	14.6	39	19.2	5.3
40	1-7Oct	26.8	13.2	40	24.9	10.4
41	8-14	26.1	12.2	41	26.5	9.8
42	15-21	26.5	13.0	42	28	10.3
43	22-28	25.3	12.1	43	26.3	9.2
44	29-4 Nov	24.9	11.8	44	23.2	8.1
45	5-11	24.4	11	45	23.4	9.0
46	12-18	20.1	8.8	46	15.2	4.3
47	19-25	21.2	7	47	18.1	9.1
48	26-2 Dec	20.2	6.1	48	15.5	8.6
49	3-9	21	8.2	49	13.9	7.5
50	10-16	19.5	8.9	50	13.9	6
51	17-23	17.7	5.8	51	12.9	8.9
52	24-31	15.9	4.8	52	12.3	4.7
1	1-7Jan	15.8	4.4	1	9.4	4.8
2	8 -14	18.2	6.6	2	14	7.7
3	15-21	18.2	7.0	3	11.7	5.9
4	22-28	14.6	3.3	4	9.1	4.5
5	29-4Feb	13.2	3.3	5	9.4	4.0
6	5-11	16.8	4.9	6	12.5	9.1
7	12-18	20.1	8.7	7	13.3	8.6
8	19-25	21.4	8.6	8	18.6	8.9
9	26-4 Mar	24.0	9.9	9	32.7	9.3
10	5-11	23.4	11.0	10	30.9	8.7
11	12-18	27.4	13.5	11	33	10.1
12	19-25	29.0	14.2	12	30.5	7.6
13	26-1Apr	27.1	13.0	13	32.8	9.9
14	2-8	29.2	16.5	14	39	8.1
15	9-15	30.7	15.7	15	44.1	8.5
16	16-22	31.3	18.0	16	48	6.2

Appendix-III

Mean weekly meteorological data for the period of experimentation during 2004-05

Standard week	Week interval	Temperature (°C)		Rainfall (mm)	Evaporation (mm)	Bright sun-shine hours
		Max.	Min.			
23	4-10 Jun	30.0	16.7	6.6	46.1	6.6
24	11-17	29.2	16.6	5.9	40.0	5.9
25	18-24	26.4	18.3	4.5	28.2	4.5
26	25-1 Jul	29.0	18.3	7.8	29.4	7.8
27	2-8	29.3	21.0	5.0	25.8	5.0
28	9-15	28.1	18.8	5.4	24.3	5.4
29	16-22	28.3	18.7	6.8	26.8	6.8
30	23-29	27.5	19.5	4.3	24.2	4.3
31	30-5 Aug	26.2	19.1	2.8	17.3	2.8
32	6-12	26.0	18.5	3.2	14.3	3.2
33	13-19	26.9	19.3	3.6	19.3	3.6
34	20-26	26.1	17.8	3.7	14.2	3.7
35	27-2Sep	28.4	18.0	8.2	24.7	8.2
36	3-9	29.2	18.6	9.2	25.5	9.2
37	10-16	26.3	18.9	3.1	17.3	3.1
38	17-23	26.7	17.2	6.6	19.0	6.6
39	24-30	27.8	16.1	8.3	23.9	8.3
40	1-7Oct	23.5	15.6	5.7	18.5	5.7
41	8-14	23.8	12.8	6.8	20.5	6.8
42	15-21	24.4	11.7	10.0	22.9	10.0
43	22-28	23.6	11.1	8.8	18.7	8.8
44	29-4 Nov	21.9	8.8	9.1	17.2	9.1
45	5-11	22.2	9.8	9.3	19	9.3
46	12-18	21.1	9.8	7.5	15.9	7.5
47	19-25	23.4	9.8	7.4	15.8	7.4
48	26-2 Dec	19.8	7.8	6.7	12.9	6.7
49	3-9	20.2	6.4	9.3	14.6	9.3
50	10-16	21.9	8.1	8.6	11.2	8.6
51	17-23	19.6	6.5	7.8	10.0	7.8
52	24-31	16.3	4.7	4.9	10.2	4.9
1	1-7Jan	17.8	5.7	4.5	8.3	4.5
2	8 -14	16.8	4.9	7.2	9.3	7.2
3	15-21	14.2	3.5	7.1	9.7	7.1
4	22-28	12.8	3.0	4.9	5.6	4.9
5	29-4Feb	16.1	5.6	7.2	11.8	7.2
6	5-11	12.7	5.9	1.0	9.0	1.0
7	12-18	15.3	6.3	3.8	7.7	3.8
8	19-25	14.7	6.0	2.9	12.5	2.9
9	26-4 Mar	19.0	10.1	4.6	16.6	4.6
10	5-11	22.0	10.1	5.5	19.2	5.5
11	12-18	22.5	12.2	6.6	22.2	6.6
12	19-25	19.8	9.6	4.8	17.7	4.8
13	26-1Apr	22.9	9.9	8.3	25.1	8.3
14	2-8	26.9	14.8	9.4	31.6	9.4
15	9-15	24.6	13.0	7.6	36.4	7.6
16	16-22	28.6	15.9	9.1	44.7	9.1
17	23-29	28.4	14.9	7.6	37.9	7.6
18	30-6 May	25.4	14.1	7.3	29.1	7.3
19	7-13	28.3	16.5	10.1	45.0	10.1
20	14-20	29.5	17.3	7.4	41.6	7.4

Appendix-IV

Genotypic coefficients of wheat (HS-240) used in DSSAT

Coefficient	P1V	P1D	P5	G1	G2	G3	PHINT
Value	0.5	3.4	2.5	10.0	2.9	2.4	95

Appendix-V

Soil mechanical separates

Treat	Depth(cm)	Control	N	NP	NPK	NPK + FYM	NPK + Lime
Sand	0-2	25.3	24.0	25.3	26.0	24.7	26.7
	2-4	23.3	20.7	22.0	21.3	22.0	22.7
	4-6	20.7	19.3	19.3	19.3	20.0	20.0
	6-8	19.3	18.7	19.3	18.7	19.3	19.3
	8-10	21.3	19.3	19.3	19.3	19.3	21.3
	10-12	24.0	21.3	22.7	23.3	22.7	23.3
	12-15	28.0	26.0	27.3	28.0	27.3	27.3
	15-30	24.0	22.7	24.7	25.3	25.3	25.3
Silt	0-2	54.0	52.7	53.3	52.0	53.3	52.7
	2-4	53.3	52.7	54.7	54.0	54.0	54.0
	4-6	54.0	52.7	54.7	54.7	54.7	54.7
	6-8	54.7	53.3	54.0	55.3	54.0	54.7
	8-10	54.0	53.3	54.7	55.3	55.3	54.0
	10-12	53.3	52.7	54.0	53.3	53.3	53.3
	12-15	51.3	52.7	52.0	52.0	52.0	51.3
	15-30	49.3	50.0	48.7	49.3	48.7	49.3
Clay	0-2	20.7	23.3	21.3	22.0	22.0	20.7
	2-4	23.3	26.7	23.3	24.7	24.0	23.3
	4-6	25.3	28.0	26.0	26.0	25.3	25.3
	6-8	26.0	28.0	26.7	26.0	26.7	26.0
	8-10	24.7	27.3	26.0	25.3	25.3	24.7
	10-12	22.7	26.0	23.3	23.3	24.0	23.3
	12-15	20.7	21.3	20.7	20.0	20.7	21.3
	15-30	26.7	27.3	26.7	25.3	26.0	25.3

Appendix-VI

Water stable aggregates (%)

Dia. >	Control	N	NP	NPK	NPK + FYM	NPK + Lime
4.00	5.40	4.92	9.92	12.89	26.00	44.79
2.00	27.65	13.99	30.44	29.37	46.13	67.17
1.00	39.85	25.17	42.10	42.13	60.43	76.78
0.50	49.72	37.28	53.04	54.67	69.96	83.20
0.25	71.04	62.89	77.46	78.57	83.60	89.59
0.10	85.18	83.58	89.44	89.27	91.00	93.77
0.00	100.0	100.0	100.0	100.0	100.0	100.0

Appendix-VII

Air-filled porosity (f_a, %)

DAS	Control		N		NP		NPK		NPK + FYM		NPK + Lime	
	θ	f_a	θ	f_a	θ	f_a	θ	f_a	θ	f_a	θ	f_a
0.06-0.09 m soil depth												
1	41.49	7.15	42.92	5.33	40.13	12.60	40.86	12.27	39.47	16.22	42.58	6.64
2	41.03	7.61	41.38	6.87	39.34	13.39	39.16	13.97	38.86	16.83	42.20	7.02
3	40.80	7.84	40.50	7.75	38.21	14.52	38.12	15.01	37.16	18.53	41.39	7.83
4	39.50	9.14	39.89	8.36	37.68	15.05	37.97	15.16	36.36	19.33	40.21	9.01
5	37.42	11.22	38.17	10.08	36.65	16.08	36.89	16.24	35.93	19.76	38.29	10.93
7	36.01	12.63	37.26	10.99	35.46	17.27	35.62	17.51	34.76	20.93	36.74	12.48
9	34.99	13.65	35.85	12.40	34.68	18.05	34.94	18.19	33.92	21.77	35.31	13.91
11	34.03	14.61	34.89	13.36	33.77	18.96	33.60	19.53	33.31	22.38	33.92	15.30
13	33.16	15.48	33.27	14.98	32.63	20.10	32.29	20.84	32.64	23.05	33.07	16.15
15	31.80	16.84	32.25	16.00	31.77	20.96	31.43	21.70	32.07	23.62	32.18	17.04
17	30.57	18.07	31.09	17.16	29.92	22.81	30.25	22.88	30.86	24.83	30.60	18.62
19	29.09	19.55	29.45	18.80	29.01	23.72	29.20	23.93	29.94	25.75	28.93	20.29
22	26.98	21.66	27.32	20.93	26.03	26.70	26.82	26.31	27.79	27.90	27.04	22.18
0.15-0.18 m soil depth												
1	42.88	2.86	43.48	1.87	42.11	4.97	42.36	5.11	42.39	6.83	41.97	3.94
2	41.95	3.79	42.29	3.06	41.34	5.74	41.93	5.54	41.57	7.65	40.93	4.98
3	40.99	4.75	41.25	4.10	40.66	6.42	40.03	7.44	40.46	8.76	40.51	5.40
4	40.65	5.09	41.01	4.34	39.82	7.26	39.58	7.89	39.80	9.42	39.82	6.09
5	39.53	6.21	40.42	4.93	38.62	8.46	38.47	9.00	38.95	10.27	38.94	6.97
7	38.87	6.87	39.55	5.80	37.82	9.26	37.98	9.49	38.01	11.21	38.21	7.70
9	37.85	7.89	38.12	7.23	36.91	10.17	37.18	10.29	36.98	12.24	37.63	8.28
11	36.82	8.92	36.94	8.41	35.82	11.26	35.63	11.84	35.82	13.40	36.58	9.33
13	35.66	10.08	36.18	9.17	34.39	12.69	34.95	12.52	34.56	14.66	35.09	10.82
15	34.79	10.95	35.67	9.68	33.58	13.50	34.21	13.26	33.81	15.41	34.27	11.64
17	33.11	12.63	33.78	11.57	32.21	14.87	32.84	14.63	32.58	16.64	32.60	13.31
19	31.65	14.09	32.11	13.24	31.47	15.61	31.37	16.10	31.39	17.83	31.23	14.68
22	28.94	16.80	29.88	15.47	28.75	18.33	28.40	19.07	28.73	20.49	28.49	17.42

DAS = Days after saturation

θ = Volumetric moisture content (%)

Appendix-VIII

Pore-size distribution (% of total)

Treatment	Pores (μm)				
	> 50	> 30	> 9	> 0.5	> 0.2
Control	20.17	31.90	38.93	53.61	61.27
N	18.79	32.00	39.01	53.04	60.32
NP	26.86	39.09	45.05	59.61	67.31
NPK	27.06	39.49	45.54	59.81	67.74
NPK + FYM	28.17	40.83	47.27	62.68	70.18
NPK + Lime	21.01	33.47	38.54	55.73	63.07
LSD (P=0.05)	2.09	1.56	1.51	1.15	1.01

Appendix-IX

Classification of pores (Greenland, 1979)

Treatment	Pores (% of total, μm)		
	>50	50-0.5	<0.5
Control	20.17	33.44	46.39
N	18.79	34.24	46.96
NP	26.86	32.75	40.39
NPK	27.06	32.75	40.19
NPK + FYM	28.17	34.51	37.32
NPK + Lime	21.01	34.72	44.27
LSD (P=0.05)	2.09	NS	1.15

Appendix-X

Soil penetration resistance (SPR, MPa)

Control		N		NP		NPK		NPK + FYM		NPK + Lime	
θ	SPR	*θ*	SPR	*θ*	SPR	*θ*	SPR	*θ*	SPR	*θ*	SPR
0.06-0.09 m soil layer											
42.43	0.34	44.24	0.28	41.47	0.42	42.13	0.36	40.75	0.42	44.52	0.30
42.26	0.40	42.73	0.42	40.89	0.45	40.62	0.54	40.22	0.69	44.13	0.41
42.02	0.52	41.94	0.58	39.91	0.82	39.91	0.72	38.56	0.60	43.61	0.48
41.82	0.68	41.17	0.42	39.53	0.59	39.66	0.57	37.92	0.49	42.53	0.67
39.81	0.79	39.47	0.64	38.34	0.78	38.48	0.70	37.47	0.66	40.68	0.86
38.42	0.85	38.58	0.94	37.04	0.74	37.25	0.86	36.47	0.79	39.15	0.65
36.86	0.50	37.05	0.61	36.36	0.66	36.64	0.62	35.66	0.67	37.18	1.01
36.16	1.28	36.16	1.24	35.46	0.94	35.19	0.55	34.98	1.06	36.05	0.88
35.26	0.63	34.45	1.16	33.99	1.14	33.55	0.64	34.15	0.95	35.17	0.49
33.41	1.05	33.70	0.84	33.06	1.24	32.64	1.16	33.67	0.83	33.79	1.42
32.31	0.97	32.65	1.19	31.23	0.85	31.55	1.33	32.39	0.89	32.34	1.24
30.70	1.22	30.91	1.31	30.38	1.38	30.67	1.09	31.46	0.60	30.54	1.25
28.63	1.47	28.69	1.38	27.19	1.29	28.01	1.43	29.28	1.21	28.69	1.42
41.95	0.50	43.50	0.47	40.80	0.70	41.32	0.64	40.08	0.48	43.04	0.60
42.03	0.48	41.98	0.57	39.85	0.58	39.66	0.47	39.54	0.52	43.20	0.42
41.72	0.56	41.37	0.69	38.82	0.50	38.74	0.60	37.79	0.38	41.31	0.40
39.63	0.65	40.86	0.59	38.06	0.53	38.37	0.42	36.90	0.34	40.34	0.83
37.57	0.98	38.96	0.49	36.92	0.44	37.15	1.09	36.18	0.50	38.44	0.54
36.10	0.72	37.95	1.02	35.87	0.90	35.86	0.70	35.05	0.55	36.83	0.64
35.28	1.04	36.72	0.69	35.05	0.54	35.46	0.89	34.21	0.65	35.60	0.95
34.36	1.55	35.73	1.15	34.06	1.20	33.95	1.07	33.56	0.87	34.25	0.65
33.60	0.79	34.32	1.11	33.02	0.96	32.82	1.09	33.07	1.07	33.51	1.14
32.56	1.02	32.84	1.34	32.04	1.31	31.89	0.83	32.41	0.90	32.94	1.45
31.22	1.32	31.54	1.45	30.12	1.20	30.66	1.37	31.22	1.33	31.25	1.40
29.83	1.59	29.93	1.41	29.18	1.36	29.62	0.92	30.34	1.22	29.67	1.29
27.95	1.50	27.81	1.56	26.37	1.46	27.27	1.45	28.35	1.07	28.01	1.53
41.17	0.42	42.64	0.67	39.55	0.77	40.38	0.71	39.00	0.76	42.26	0.51
40.90	0.64	40.92	0.73	38.70	0.60	38.43	0.87	38.11	0.71	42.07	0.48
40.71	0.79	39.95	0.60	37.56	0.90	37.37	0.41	36.44	0.54	41.30	0.23
39.20	0.55	39.45	0.49	37.31	0.72	37.57	0.52	36.04	0.50	39.91	0.42
37.00	0.61	37.64	0.58	36.45	0.42	36.61	0.60	35.85	0.74	37.87	0.70
35.46	0.59	36.71	0.87	35.25	0.85	35.58	0.47	34.68	0.82	36.19	0.95
34.59	1.31	35.48	1.32	34.34	1.04	34.55	0.86	33.86	1.07	34.91	1.08
33.53	1.04	34.55	1.24	33.47	0.68	33.44	0.95	33.29	0.85	33.42	1.26
32.57	1.17	33.31	1.08	32.60	1.08	32.27	0.78	32.53	0.74	32.48	1.27
31.17	1.24	32.26	1.43	31.78	1.21	31.42	1.18	31.74	1.15	31.55	1.63
29.82	1.38	31.07	1.21	29.80	1.45	30.11	1.10	30.53	1.03	29.85	1.32
28.37	1.44	29.30	1.40	28.73	1.10	28.97	1.39	29.42	1.15	28.21	1.17
25.90	1.60	26.97	1.67	25.56	1.52	26.56	1.58	27.13	1.36	25.96	1.51
40.41	0.52	41.31	0.61	38.70	0.66	39.60	0.51	38.06	0.55	40.50	0.52
38.95	0.55	39.89	0.64	37.91	0.72	37.94	0.45	37.57	0.69	39.42	0.74
38.76	0.66	38.76	0.72	36.54	0.56	36.46	0.58	35.85	0.57	39.35	0.35
37.36	0.79	38.09	0.62	35.84	0.68	36.28	0.97	34.59	0.67	38.07	0.45
35.32	1.27	36.60	0.57	34.91	0.93	35.32	0.81	34.21	0.91	36.19	1.16
34.05	1.09	35.79	0.97	33.69	0.94	33.79	1.04	32.86	1.00	34.78	1.11
33.24	0.91	34.15	1.18	32.99	1.03	33.11	1.29	31.95	1.24	33.56	1.38
32.08	1.35	33.14	1.41	32.11	1.01	31.83	0.93	31.41	0.83	31.97	1.01
31.22	1.21	31.00	1.52	30.93	1.32	30.51	1.22	30.81	1.18	31.13	1.32
30.08	1.02	30.21	1.09	30.21	1.55	29.76	1.01	30.48	0.79	30.46	1.10
28.93	1.41	29.09	1.53	28.55	1.12	28.70	1.28	29.30	1.21	28.96	1.38
27.48	1.58	27.65	1.36	27.75	1.31	27.55	1.39	28.55	1.34	27.32	1.46
25.44	1.57	25.83	1.55	25.01	1.59	25.44	1.51	26.40	1.45	25.50	1.52

contd….

Control		N		NP		NPK		NPK + FYM		NPK + Lime	
θ	SPR	θ	SPR	θ	SPR	θ	SPR	θ	SPR	θ	SPR
0.15-0.18 m soil layer											
44.82	0.44	44.80	0.52	43.45	0.54	43.63	0.46	43.67	0.50	43.91	0.48
43.88	0.66	43.64	0.56	42.89	0.71	43.39	0.61	42.93	0.67	42.86	0.47
43.21	0.77	42.69	0.83	42.36	1.07	41.82	0.97	41.86	0.85	42.73	0.73
42.97	0.83	42.29	0.77	41.67	0.79	41.27	0.72	41.36	0.64	42.14	0.88
41.92	1.15	41.72	1.00	40.31	1.14	40.06	0.98	40.49	1.04	41.33	1.12
41.28	0.82	40.87	1.13	39.40	1.11	39.61	1.30	39.72	1.26	40.62	1.21
39.72	1.07	39.32	1.18	38.59	1.23	38.88	1.19	38.72	1.24	39.50	1.28
38.95	1.44	38.21	1.54	37.51	1.29	37.22	1.16	37.49	0.96	38.71	1.20
37.76	1.49	37.36	1.60	35.75	1.40	36.21	1.30	36.07	1.26	37.19	1.15
36.40	1.73	37.12	1.52	34.87	1.92	35.42	1.84	35.41	1.51	35.88	1.52
34.85	1.67	35.34	1.70	33.52	1.25	34.14	1.45	34.11	1.08	34.34	1.60
33.26	1.14	33.57	1.23	32.84	1.13	32.84	1.01	32.91	1.27	32.84	1.17
30.59	1.59	31.25	1.25	29.91	1.81	29.59	1.65	30.22	1.58	30.14	1.74
43.34	0.58	44.06	0.53	42.78	0.76	42.82	0.70	43.00	0.56	42.43	0.86
42.95	0.72	42.89	0.81	41.85	0.61	42.43	0.51	42.25	0.47	41.93	0.76
40.91	1.08	42.12	1.21	41.27	1.02	40.65	1.12	41.09	0.70	40.43	0.52
40.78	1.10	41.98	1.04	40.20	0.98	39.98	0.87	40.34	0.79	39.95	1.28
39.68	1.01	41.21	1.08	38.89	1.03	38.73	0.94	39.20	0.91	39.09	1.09
38.96	1.24	40.24	1.42	38.23	1.30	38.22	1.49	38.30	1.45	38.30	0.77
38.14	1.21	38.99	1.12	37.28	0.97	37.70	1.13	37.27	1.08	37.92	1.38
37.15	1.29	37.78	1.89	36.11	1.55	35.98	1.51	36.07	1.41	36.91	1.59
36.10	0.79	37.23	0.90	34.78	1.60	35.48	0.88	34.99	0.86	35.53	0.93
35.55	1.82	36.26	1.61	33.85	1.76	34.67	1.63	34.15	1.70	35.03	1.45
33.76	1.44	34.23	1.37	32.41	1.12	33.25	1.32	32.94	1.25	33.25	1.32
32.39	1.26	32.59	1.62	31.64	1.28	31.79	1.13	31.79	1.08	31.97	1.50
29.91	1.72	30.37	1.68	29.09	1.56	28.85	1.87	29.29	1.55	29.46	1.72
42.56	0.64	43.20	0.61	41.53	0.71	41.88	0.65	41.92	0.70	41.65	0.78
41.82	0.77	41.83	0.86	40.70	0.50	41.20	1.00	40.82	0.84	40.80	0.61
40.90	1.21	40.70	1.22	40.01	1.18	39.28	1.03	39.74	1.16	40.42	0.85
40.35	1.12	40.57	1.06	39.45	0.89	39.18	0.78	39.48	0.70	39.52	1.20
39.11	1.32	39.89	1.39	38.42	1.10	38.19	1.01	38.87	0.96	38.52	1.41
38.32	1.51	39.00	1.29	37.61	0.97	37.94	1.19	37.93	0.65	37.66	1.07
37.45	0.95	37.75	0.96	36.57	1.38	36.79	1.14	36.92	1.09	37.23	1.52
36.32	1.20	36.60	1.40	35.52	0.84	35.47	1.11	35.80	1.01	36.08	1.42
35.07	0.91	36.22	0.99	34.36	1.02	34.93	0.72	34.45	0.68	34.50	1.21
34.16	1.27	35.68	1.46	33.59	1.24	34.20	1.21	33.48	1.18	33.64	1.76
32.36	1.82	33.76	1.52	32.09	1.28	32.70	1.48	32.25	1.41	31.85	1.70
30.93	1.86	31.96	1.87	31.19	1.85	31.14	1.63	30.87	1.58	30.51	1.65
27.86	1.94	29.53	1.75	28.28	1.78	28.14	1.62	28.07	1.70	27.41	1.85
40.80	0.88	41.87	0.85	40.68	0.66	41.10	0.87	40.98	0.71	39.89	0.91
39.17	1.05	40.80	1.14	39.91	0.86	40.71	0.75	40.28	0.99	38.15	1.24
38.95	1.44	39.51	1.50	38.99	1.23	38.37	1.13	39.15	1.05	38.47	1.10
38.51	1.54	39.21	1.46	37.98	1.51	37.89	1.31	38.03	0.91	37.68	1.29
37.43	1.25	38.85	0.87	36.88	1.23	36.90	1.11	37.23	1.21	36.84	1.46
36.91	1.32	38.08	1.50	36.05	1.47	36.15	1.57	36.11	1.53	36.25	1.64
36.10	1.46	36.42	1.27	35.22	1.12	35.35	1.38	35.01	1.33	35.88	1.47
34.87	1.49	35.19	1.69	34.16	1.29	33.86	1.21	33.92	1.11	34.63	1.29
33.72	1.81	33.91	1.92	32.69	1.72	33.17	1.62	32.73	1.58	33.15	1.72
33.07	1.24	33.63	1.12	32.02	1.59	32.54	1.05	32.22	0.83	32.55	1.15
31.47	1.60	31.78	1.73	30.84	1.28	31.29	1.48	31.02	1.41	30.96	1.68
30.04	1.72	30.31	1.81	30.21	1.71	29.72	1.59	30.00	1.54	29.62	1.66
27.40	2.04	28.39	2.12	27.73	1.92	27.02	1.98	27.34	1.92	26.95	2.01

θ = Volumetric moisture content (%)

Appendix-XI

Soil water retention (Mass basis)

Treatment	Matric suction (kPa)					
	0	6	10	33	600	1500
Control	41.2	32.9	28.1	25.2	19.1	16.0
N	41.2	33.4	28.0	25.1	19.3	16.3
NP	49.6	36.2	30.2	27.2	20.0	16.2
NPK	50.4	36.7	30.5	27.4	20.2	16.3
NPK + FYM	56.4	40.6	33.4	29.8	21.1	16.8
NPK + Lime	43.8	34.6	29.1	26.9	19.4	16.2
LSD (P=0.05)	0.7	0.7	0.4	0.5	0.6	0.4

Soil water retention (Volume basis)

Treatment	Matric suction (kPa)					
	0	6	10	33	600	1500
Control	53.2	42.4	36.2	32.5	24.7	20.6
N	53.5	43.4	36.4	32.6	25.1	21.2
NP	60.0	43.9	36.5	32.9	24.2	19.6
NPK	60.4	44.1	36.6	32.9	24.3	19.5
NPK + FYM	63.2	45.4	37.4	33.3	23.6	18.9
NPK + Lime	56.1	44.3	37.3	34.5	24.8	20.7
LSD (P=0.05)	0.9	0.8	0.5	0.6	0.6	0.5

Appendix-XII

Infiltration characteristics

Control			N			NP		
CT	*I*	*i*	CT	*I*	*i*	CT	*I*	*i*
10	16.09	96.56	10	15.66	93.96	10	18.85	113.09
20	24.10	48.05	20	22.94	43.66	20	31.19	74.03
40	34.45	31.03	50	37.55	29.23	40	44.43	39.74
100	54.84	20.39	80	47.39	19.68	70	60.26	31.64
160	70.22	15.38	140	62.41	15.02	130	85.54	25.28
220	83.95	13.73	200	76.03	13.62	190	107.19	21.65
280	97.24	13.29	260	89.07	13.04	250	127.10	19.91
340	110.40	13.16	320	101.77	12.69	310	146.85	19.76
370	116.98	13.15	350	108.05	12.58	370	166.54	19.68

NPK			NPK+FYM			NPK+LIME		
CT	*I*	*i*	CT	*I*	*i*	CT	*I*	*i*
10	19.12	114.70	10	28.56	171.34	10	17.63	105.80
20	32.30	79.11	20	43.75	91.17	20	26.17	51.22
50	53.21	41.81	50	76.50	65.50	50	42.24	32.13
80	69.22	32.02	80	101.39	49.78	110	65.30	23.06
110	81.74	25.05	140	139.55	38.16	170	84.20	18.90
170	103.69	21.94	200	172.03	32.49	230	99.18	14.97
230	124.50	20.81	260	200.15	28.12	290	113.06	13.89
290	145.22	20.72	320	227.05	26.90	350	126.76	13.70
350	165.75	20.53	350	240.46	26.81			

CT = cumulative time (minutes)
I = Cumulative infiltration (mm)
i = Infiltration rate (mm h^{-1})

Appendix-XIII

In-situ layer-wise water percolation

Treatment	Layer-wise percolation rate (x 10^{-6} ms^{-1})				
	0-0.05 m	0.05-0.10 m	0.10-0.15 m	0.15-0.20 m	0.20-0.25 m
Control	45.13	28.28	10.44	11.69	15.84
N	46.59	23.92	9.63	9.29	13.69
NP	38.94	34.76	22.25	19.31	20.81
NPK	41.01	38.19	24.99	17.47	19.15
NPK + FYM	68.97	60.01	35.93	23.28	24.06
NPK + Lime	29.84	20.43	11.77	16.70	25.11
LSD (P=0.05)	6.10	7.99	4.66	4.15	5.61

Appendix-XIV

Crop water use during wheat season

Profile water use (2003-04)

Phenological stage	Control	N	NP	NPK	NPK + FYM	NPK + lime
Sowing-Tillering	12.12	8.38	13.73	14.86	15.56	14.83
Tillering-Flowering	-11.59	-19.98	-4.98	-2.05	1.54	1.18
Flowering-Physiological Maturity	70.47	58.70	85.21	87.31	109.97	110.71
Physiological Maturity-Harvest	37.87	26.37	49.79	48.91	54.84	50.34
Sowing-Harvest	108.88	73.46	143.74	149.02	181.91	177.05

Total water use (2003-04)

Phenological stage	Control	N	NP	NPK	NPK + FYM	NPK + lime
Sowing-Tillering	63.62	59.88	65.23	66.36	67.06	66.33
Tillering-Flowering	360.91	352.52	367.52	370.45	374.04	373.68
Flowering-Physiological Maturity	160.77	149.00	175.51	177.61	200.27	201.01
Physiological Maturity-Harvest	39.97	28.47	51.89	51.01	56.94	52.44
Sowing-Harvest	625.28	589.86	660.14	665.42	698.31	693.45

Profile water use (2004-05)

Phenological stage	Control	N	NP	NPK	NPK + FYM	NPK + lime
Sowing-Tillering	3.42	2.84	10.34	10.72	11.24	10.54
Tillering-Flowering	3.95	3.01	10.04	10.58	14.94	13.15
Flowering-Physiological Maturity	-5.36	-8.48	0.75	1.02	6.71	5.06
Physiological Maturity-Harvest	68.73	61.44	96.20	99.99	108.04	106.56
Sowing-Harvest	70.75	58.81	117.34	122.31	140.93	135.31

Total water use (2004-05)

Phenological stage	Control	N	NP	NPK	NPK + FYM	NPK + lime
Sowing-Tillering	89.42	88.84	96.34	96.72	97.24	96.54
Tillering-Flowering	519.25	518.31	525.34	525.88	530.24	528.45
Flowering-Physiological Maturity	114.54	111.42	120.65	120.92	126.61	124.96
Physiological Maturity-Harvest	106.83	99.54	134.30	138.09	146.14	144.66
Sowing-Harvest	830.05	818.11	876.64	881.61	900.23	894.61

Appendix-XV

Root mean square error (RMSE) for observed and simulated values of moisture content during wheat season (2004-05)

Depth	Control	N	NP	NPK	NPK + FYM	NPK + lime
0-0.05 m	0.076	0.062	0.062	0.058	0.047	0.077
0.05-0.15 m	0.064	0.049	0.066	0.064	0.063	0.074
0.15-0.30 m	0.066	0.049	0.062	0.056	0.058	0.062
0.30-0.45 m	0.055	0.046	0.063	0.058	0.066	0.056
0.45-0.60 m	0.038	0.031	0.046	0.044	0.056	0.048
0.60-0.90 m	0.047	0.044	0.049	0.042	0.052	0.048

Appendix-XVI

Simulated and Observed moisture content in 0-0.90 m soil layer during 2004-05

	Control		N		NP	
	Sim	Obs	Sim	Obs	Sim	Obs
Sowing	0.345	0.367	0.354	0.368	0.325	0.370
Tillering	0.292	0.364	0.303	0.365	0.289	0.358
Flowering	0.305	0.359	0.326	0.361	0.293	0.347
Physiological Maturity	0.301	0.365	0.318	0.370	0.293	0.346
Harvest	0.286	0.290	0.295	0.303	0.282	0.240

	NPK		NPK + FYM		NPK + Lime	
	Sim	Obs	Sim	Obs	Sim	Obs
Sowing	0.321	0.360	0.326	0.370	0.324	0.368
Tillering	0.288	0.348	0.290	0.358	0.288	0.356
Flowering	0.293	0.336	0.295	0.341	0.293	0.342
Physiological Maturity	0.292	0.335	0.294	0.333	0.292	0.336
Harvest	0.281	0.225	0.283	0.214	0.281	0.219

Appendix-XVII

NLWR and wheat grain yield

NLWR	Wheat grain yield (Mg ha^{-1})	
	2003-04	2004-5
9.34	0.44	0.45
7.43	0.00	0.00
12.40	1.05	2.88
13.86	1.80	2.85
18.94	2.52	3.67
8.34	2.43	3.77
8.93	0.25	0.73
7.99	0.00	0.00
12.05	1.18	2.90
12.71	1.72	2.75
16.17	2.27	3.50
9.93	2.07	2.92
8.86	0.38	0.46
8.09	0.00	0.00
11.21	1.05	1.67
12.18	2.02	2.72
16.59	2.35	3.47
9.28	2.12	2.47
9.00	0.32	0.72
7.10	0.00	0.00
13.08	1.10	1.73
13.77	1.43	2.53
14.48	2.17	2.68
9.95	2.67	3.27

Appendix-XVIII

Ammonical and nitrate nitrogen

Nitrogen (mg kg^{-1})	Depth (m)	Control	N	NP	NPK	NPK + FYM	NPK + lime
Ammonical	0-0.05	9.8	11.7	19.4	22.3	29.2	21.4
	0.05-0.15	7.8	9.8	11.7	11.7	21.4	13.6
Nitrate	0-0.05	5.8	7.8	17.5	19.4	23.3	15.6
	0.05-0.15	4.8	5.8	7.8	9.8	13.6	11.7