CARBON SEQUESTRATION AND NUTRIENT DYNAMICS IN A LONG-TERM LANTANA AMENDED SOIL UNDER RICE- WHEAT SYSTEM

THESIS

By

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CERTIFICATE – I

This is to certify that the thesis entitled **"Carbon sequestration and nutrient dynamics in a long-term lantana amended soil under rice-wheat system"**, submitted in partial fulfillment of the requirements for the award of the degree of **Doctor of Philosophy (Agriculture)** in the subject of **Soil Science** of CSK Himachal Pradesh Agricultural University, Palampur is a bonafide research work carried out by **Ms Bharti Raina (A-2003-40-6)** daughter of **Shri C.L. Raina** 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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CERTIFICATE – II

This is to certify that the thesis entitled **"Carbon sequestration and nutrient dynamics in a long-term lantana amended soil under rice-wheat system"**, submitted by **Ms Bharti Raina (A-2003-40-6))** daughter of **Shri C.L. Raina** to CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur, in partial fulfillment 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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(Bharti Raina)

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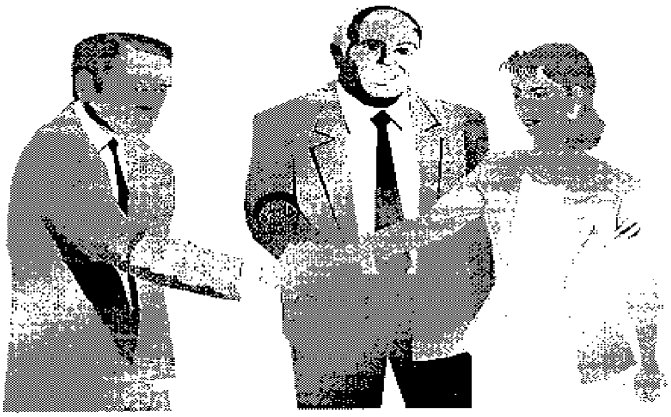


Introduction

Chapter I

INTRODUCTION

Agricultural land management in the past especially after mid sixtees has stressed the soil system, often withdrawing more than what was returned. The land area under agriculture is shrinking in India while demand for food is increasing. The per capita availability of cultivable land is expected to reduce to about 0.14 ha by 2025 from the present level of about 0.17 ha (Singh, 1999). The projected doubling of the human population in the next century threatens even greater degradation of soils and other natural resources (Mishra, 2005). It has raised an issue of sustaining agricultural production system all over the world. The goal of assessment of sustainability is to quantify the impact of management on soil quality and processes relevant to agronomic productivity and environmental quality (Lal, 1994).

Soil quality is directly related to Soil Organic Carbon (SOC) content (Lal, 2006). Enhancing SOC concentration in soils improves both soil and crop productivity by way of improving soil physical, chemical and biological properties and thus overall soil quality (Bhattacharya *et al.*, 2000, Singh *et al.*, 2003). Soil contains about 75% of the terrestrial carbon and plays an important role not only in crop production but also in managing carbon concentration in atmosphere. About 110 gigatons per year of carbon is absorbed from the atmosphere into plant life through the process of photosynthesis. Of that amount, about 60 gigatons of carbon is again released into the atmosphere through respiration, decay and gaseous waste elimination from living animal biomass. The remaining 50 gigatons is incorporated into the soil, part of which can be readily oxidized and

part of which is relatively stable for many years (Anonymous, 1999). The bottom line of all this is that the amount of carbon in the atmosphere is increasing by about 6.1 gigatons per year, and it is believed that there is a direct relationship between increased levels of carbon dioxide in the atmosphere and rising global temperature. If present trends continue unabated, it is estimated that carbon dioxide levels would reach 600 ppm in 2100,1300 ppm in 2200 and level off at 1800 ppm in the year 2400 (Harvey and Danney, 2000). Thus, it will have a direct effect on global hydrological cycle and alter the distribution and productivity of terrestrial biota. Therefore, this increase needs to stop or at least slow down. In this context, storage of carbon in the soil system has attracted attention of scientists world over not only because of its potential to mitigate global warming but also because of its importance as a source and sink for different nutrients in Soil. So carbon (C) sequestration in the soil is one of the major factors responsible for restoring and sustaining the soil health (Chan and Heenan, 2005, Rudrappa *et al.*, 2005).

Most of the cropped soils of India contain low levels of SOC concentration. Regular additions of organic materials to soil, therefore, are required to improve and maintain carbon pools and their activities. The farmyard manure and composts are the main sources in Indian soils, but they are in short supply due to one or the other reasons. The substitution of FYM (and other limited organic sources) with locally available waste organic materials which are of less economic value is envisaged for soil carbon sequestration. All hill and mountain agro-ecosystems, including Himachal Pradesh are endowed with a variety of waste biomass that has limited utility either as fodder, fuel, fibre or energy. They can serve as potential carbon sources in soils. The prevailing low temperatures in hills provide added opportunity for Soil Organic Matter (SOM) build up.

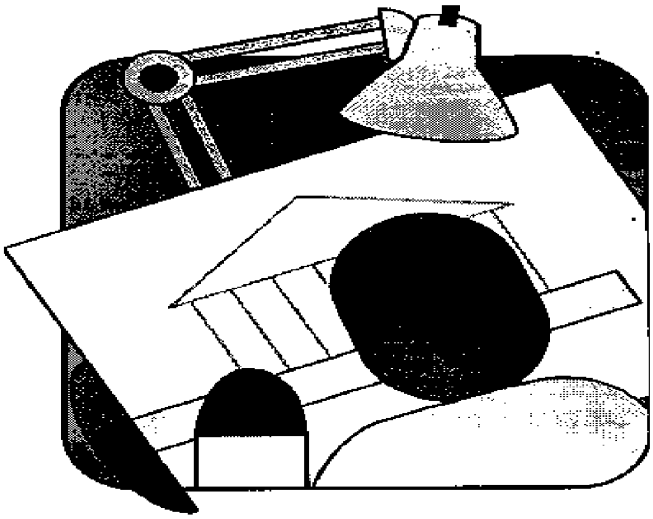
There is a growing concern regarding the quality of SOM besides its quantitative estimates in soils (Gregorich *et al.*, 1994). Cassman *et al.* (1997) raised the issue of decline in quantity of SOC in wetland soils impacting native N availability to rice. Nearly 98% of all native soil N is in SOM, but in spite of conservation of SOM in the long-term experiments rice yields declined. Hence, characterization of SOC quality is important to get insights into the causes of decreasing system performance in spite of maintaining SOC pools. The quality of SOM has often been linked with its functional pool vis-à-vis its turnover over the time. Small changes in total SOM are, however, difficult to detect because of large background levels and natural soil variability (Blair *et al.*, 1995; Carter, 2002). Attempts, therefore, have been made to use sub-pools of SOM as most sensitive indicators of change in pool size. These are the active and passive organic pools of the SOM, which act as highly sensitive indicators of soil fertility and productivity. By comparison, active pool of SOM is most important in providing energy for biological processes while humus is an important source of essential nutrients. The build up in these pools of SOM is a slow process and may take even more than 30 years for any noticeable change as a result of different management practices (Baldock and Skjemstad,1999). Long-term field experiments, therefore, provide great pathway to study different pools of organic matter in soils.

The SOM modeling is gaining recognition to understand and manage the terrestrial carbon cycle. These models help in predicting changes in C-sequestration for coming years within short span of time. Various workers have developed a number of carbon models predicting carbon turnover under different management practices (Parton *et al.*, 1987; Jenkinson, 1990; Smith *et al.*, 1997). The Global Changes and Terrestrial Ecosystems-Soil Organic Matter Network

(GCTE- SOMNET) includes Roth-C- 26.3 model for prediction of C stocks. The Roth-C- 26.3 and CANDY carbon models have been validated under tropical and semi-arid situations and hold promise in predicting C turn over (Singh *et al.*, 2003). The C-sequestration pattern in temperate climatic conditions, however, is different than tropical situations and the information on validation of these C models under temperate conditions in general and rice-wheat cropping system in particular is still lacking. The validation of these models assumes great significance from management point of view and as indicator of soil quality.

The information on the effect of organic amendments and mineral fertilizers on organic pools of the nutrients is scanty and thus, calls for taking an immediate stock of carbon dynamics. Long-term fertilizer experiments provide a unique opportunity for such studies (Manna *et al.*, 1996). The information in the wet-temperate regions is, however, lacking. Therefore, systematic studies are needed to understand C- sequestration processes, quality and quantity issues and their impact on soil, environment and crop productivity. With this background, the present study entitled "*Carbon sequestration and nutrient dynamics in a long-term lantana amended soil under rice- wheat system*" was planned under wet- temperate zone of Himachal Pradesh with the following objectives:

1. To asses the changes in C-sequestration and long term effect of organic and inorganic fertilizers on pools of SOM, N, P and S.
2. To work out the relationship between SOM pools, nutrients' supply and crop productivity
3. To fit the data on SOM pools in GCTE-SOMNET and CANDY models of C-sequestration.



Review of Literature

Chapter II

REVIEW OF LITERATURE

Soil Organic Matter (SOM) has a comprehensive effect on the physical, chemical and biological properties of soils. It acts as a source and sink for nutrient elements which can form organic moieties (N, P, S). It has charge as well as physical and chemical properties which facilitates ion-exchange, aggregation with mineral particles, influences soil water regimes and a source of energy for soil biota. Furthermore, as a part of global C reservoir, SOM interacts with the atmosphere and through affecting its CO_2 content, it influences the overall state of the environment. Thus, SOM itself represents a set of attributes rather than an entity.

Although soils can be a net sink for C, yet available data indicate that managed soils have historically been a net source of atmospheric CO_2 (Schlesinger and Andrews, 2000) contributing to more than 20 percent of the annual CO_2 increase (3.2 Pg C; Watson *et al.*,1992) in the atmosphere. A reduction in the rate of CO_2 accumulation in the atmosphere can be achieved through enhancement of long-term carbon sequestration in the terrestrial biosphere through proper maintenance of SOM. Keeping in view the importance of SOM, the pertinent literature regarding changes in C-sequestration and pools of SOM-N, P and S has been reviewed in this chapter under the following sub-heads:

2.1 Effect of Integrated use of Organic Manures and Chemical Fertilizers

2.1.1 Soil Organic Matter (SOM) Pools

2.1.1.1 Soil organic carbon

2.1.1.2 Active pools of soil organic matter

2.1.1.3 Slow pools of soil organic matter

2.1.1.4 Passive pools of soil organic matter

2.1.1.5 Passive pools of nutrients

2.1.2 Microbial Environment of Soils

2.1.2.1 Soil microbial biomass

2.1.2.2 Microbial count

2.1.3 Carbon Sequestration and SOM Dynamics

2.2 Relationship between SOM Pools, Nutrients' Supply and Crop Productivity

2.3 Validation of Carbon Models

2.1 Effect of Integrated use of Organic Manures and Chemical Fertilizers

2.1.1 Soil Organic Matter (SOM) Pools

Soil contains three times as much carbon as the atmosphere. Therefore, the balance between soil carbon inputs and outputs has critical influence on the concentration of atmospheric CO_2 (Post *et al.*, 1999). The rate at which carbon is cycled between the soil atmosphere is partly dependent on the carbon compounds present in SOM (Lal, 1997; Izaurralde *et al.*, 2001). Stable, intermediate and active carbon compounds comprise the SOM pool. These three forms are found in varying proportion in soil with the least digestible (lignin) and chemically stable organic matter (humus) making almost all of the stable organic

matter pool (Jastrow *et al.*, 1996; Amelung *et al.*, 1998). Live and dead organisms and partially decomposed organic matter (Bremer *et al.*, 1994; Paul and Clark, 1996) make up the active fraction. The chemical association of organic matter and mineral particles in soil make the sequestered carbon less accessible to soil organisms, thereby leading to less carbon mineralization (Kay, 1998). Christopher *et al.* (2004) determined the effects of long-term elevated N on the stability of five organic matter pools and indicated the stabilization of organic matter in all soil fractions over the years. The effect of fertilization and amendments on these SOM pools is described under the following sub-heads:

2.1.1.1 Soil Organic Carbon (SOC)

Soil organic carbon is considered to be one of the most important pools of soil organic matter. Amount and nature of SOC play a key role in soil quality (Larson and Pierce, 1992). Although organic carbon is not a plant nutrient, its low concentrations (0.5-1% by weight) can have deleterious effect on crop productivity (Stevenson, 1982). The depletion of SOC reserves has been cited as a serious threat to the maintenance of soil quality. Yadav *et al.* (2000) reported more than 50 per cent decline in soil loss and increase in SOC by applying crop residues as mulch. Several reports have shown that active fraction incurred proportionately higher losses of SOC than the stable more humified fraction (Ladd and Russell, 1983). Long-term experiments have shown the benefits of manure, adequate fertilization and crop rotations on soil carbon content (USDA, 2005). Long-term studies have consistently shown the benefit of manures, adequate fertilization and crop rotation on maintaining agronomic productivity by increasing C inputs into the soil. Application of organic fertilizers on the other hand, elicits increasing organic carbon and positively change other chemical

characteristics associated with soil fertility (Mazur *et al.*, 1983; Ferreira and Cruz, 1992; Alves *et al.*, 1999). Subsequent annual application of farmyard manure (FYM) increased SOC from 1 to 3.4 per cent whereas long-term application of N had no measurable effect on SOC levels over the years (Johnston, 1991). Similarly, Paustian *et al.* (1992) in a thirty years Swedish trial, showed positive effects of biannual addition of various organic carbon residues viz; straw, green manure and FYM on SOC content. Long-term experiments at various places in India showed that integrated use of fertilizers and manure for about twenty years increased the SOC content in 0-15 cm layer by 0.2 to 0.5 per cent (Nambiar, 1995). Raupp (1999) studied the effect of manures and mineral fertilizers on the maintenance of SOC under long-term trial established in 1923 and reported the organic carbon content to be higher with manure (0.90%) than with mineral fertilization (0.79%). The manure treatments contained 4 to 8 t ha^{-1} more carbon in the top soil than the mineral fertilized plots. In addition, the increase in pH affects the dynamics of SOM fractions leading to de-polymerization of humic acid and to a small increase in fulvic acid (Araujo *et al.*,1995). Soil acidification could result in decreased decomposition of OM (Paustian *et al.*, 1997), thus having positive effect on soil C sequestration. Belanger *et al.* (1989) also observed similar kind of negative slope between soil carbon concentration and soil reaction.

On the contrary, Reeves (1997) has reported that continuous cropping even with crop rotation and manure addition results in decline in SOC. The rate and magnitude of decline is influenced by cropping and tillage system, climate and soil. The application of N alone continuously for more than thirty years had deleterious effect on SOC (Kaushal, 2002; Sharma *et al.,* 2002). The rate of

increase in SOC pool could be more for initially low antecedent SOC (Follett, 2001). However, sub-optimal levels of fertilizer application in tropics might cause reduction in SOC pool. Selvi *et al.* (2003) reported that continuous manuring and fertilization for more than thirty years results in about 40 per cent gain in SOC. Similar build up in SOC has been observed by many other workers (Schjonning *et al.*, 1994; Bowman and Halvorson, 1998; Kundu *et al.*, 2001).

Incorporation of crop residues and FYM helps in enhancing the SOC level. Inputs of these organic materials via roots and root exudates increase with crop yield and hence increase SOC content in fertilized over unfertilized treatments (Duxbury *et al.*, 2000). *Glyricidia* application to crop lands to meet out 50 per cent NPK requirement results in significantly higher SOC content over other fertilized lands (Bellaki *et al.*, 1998). The application of 22 Mg ha^{-1} compost and 45 Mg ha^{-1} beef cattle (*Bos taurus* L.) manure for 4 to 5 years has increased the total carbon by 28 per cent in 1996 and 46 per cent in 1997 relative to un-amended plots (Grandy *et al.*, 2002).

Soil organic carbon decreases linearly or curvilinearly under all cropping systems and fertility treatments. However, addition of lime and NPK to previously unfertilized plots increased the biomass and crop residues resulting in reversal of SOC decline (Odell *et al.*, 1984). Mitchell *et al.* (1991) summarized the soil fertility findings from the Magruder plots and reported that SOC and accompanying soil N, declines rapidly during first thirty five years of fertilization and somewhat more slowly during next fifty two years. Application of manure slowed the decline but could not prevent the loss of SOC and soil N. Furthermore, lack of fertilization and resulting decrease in biomass after 90 years

of cropping of winter wheat-beet-barley-clover-grass returned less carbon to the soil and consequently diminished several physical indicators of soil quality such as bulk density (Schjonning *et al.*, 1994). Robinson *et al.* (1996) concluded that carbon systems with the ability to conserve soil organic carbon could sequester up to 30 per cent of carbon released since the beginning of cropping and thereby increase soil organic carbon with the addition of manure and lime for about thirty five years.

Increasing doses of FYM application have synergistic effect on SOC content for twenty years. The organic carbon content, however, was reported to be less in treatments receiving inorganic N as the latter enhanced the decomposition of the former (Kukreja *et al.*, 1991). The results of ten year long-term experimentation on stability and activity of SOC showed that the oxidizable organic matter, active organic matter and co-efficient of oxidizable stability all increases with the continuous application of organic manures as well as with the integrated use of organics and inorganics. However, chemical fertilizers alone have little positive effect on the oxidizable soil organic carbon (Zhang, 1996).

Janzen (1987) reported about 14 per cent increase in SOC content in N fertilized plots compared to plots receiving no N after eighteen years of long-term crop rotation. Phosphorus fertilization, however, had no significant influence on this attribute. Paustian *et al.* (1997) and Belanger *et al.* (1999) on the other hand, observed no response of soil carbon to N fertilization even after thirty five years of intensive cropping and attributed the same to relatively high soil carbon content and thus possible saturation of carbon retention in the soils.

Powlson *et al.* (1998) described the Global Change and Terrestrial Ecosystems (GCTE) - Soil Organic Matter Network (SOMNET) based on data on soil quality parameters of long-term experimental sites. They suggested that amending arable soil with 10 Mg ha^{-1} of organic manure could lead to an increase of 4.8 per cent in soil carbon stock to 30 cm depth over a period of 90 years with limited potential for sequestering carbon. Nitrogen application increased crop residue inputs to the soil resulting in increase in total soil nitrogen and SOC after eleven crops. The increase in SOC decreased the bulk density, thus improving the carbon sequestration. The long-term observations showed that the amount of soil organic matter is primarily a function of the prevailing land use. Clearly marked differences have been observed between long-term arable farming with low SOC and short-term farming with higher soil organic carbon content. Agricultural practices lead to decrease in soil organic carbon with the result that arable soils act as source of carbon rather than sink.

Campbell *et al.* (2000) observed sharp increase in SOC content with the application of N and P fertilizers in the annual crop rotations. Soil organic carbon content as well as aggregate size distribution of soil have been improved with increasing rates of NPK fertilizers while water resistance of soil aggregates deteriorated under similar set of treatments. Results of about fifty years' fertilization have indicated that long-term application of chemical fertilizers slightly increases the SOC content compared to soil without fertilizers application (Chen and Lian, 2002). Rogasik *et al.* (2004) calculated the optimum values of organic fertilizer application for maintaining soil organic carbon and indicated that

combination of organic and mineral fertilization increase the soil organic carbon content compared to exclusive mineral fertilization. They, however, reported decline in the soil carbon pool with the application of lime in large amounts.

The assessing effects of long-term cropping system on soil carbon change have been found to be essential to make projections regarding sequestration emission of CO_2 by agricultural soils. Thus, long-term fertilizer experiments are a useful tool for calculating the carbon sink or source potential of arable soils.

2.1.1.2 Active Pools of Soil Organic Matter

2.1.1.2.1 Water-soluble organic carbon (WS-OC): Water-soluble organic carbon (WS-OC) appears to be the immediate organic substrate for soil microorganisms (McGill *et al.*, 1981). Changes in WS-OC, which is the most labile and mobile form of SOC, have received much less attention. Concentrations of water-soluble and bio-available SOC have been reported to be high in agricultural soils (Boyer and Groffiman, 1996). These data suggested that agricultural soils might support greater rate of microbial activity than forest soils due to increased production of water-soluble carbon. Long-term influence of cropping practices has been expected to affect various replenishment mechanisms, thereby altering WS-OC supply. Results of forty years of continuous conventional cropping indicated significant reduction in the content of alkali extractable and water-soluble carbon as compared to grassland soils (Saviozzi *et al.*, 1994). Long-term fertilization with NPK + farmyard manure for eighty-eight years has resulted in larger mean concentrations of hot water-extracted C and N (0.933 and 0.094 g kg^{-1}) than soil management without

fertilization (0.511 and 0.056 g kg^{-1}). The C and N extracted by hot water were in the range of 3-5 per cent of total soil C and N (Leinweber *et al.*, 1995). Kreutzer (1995) obtained an increase in this organic carbon content dissolved with liming in a spruce stand for eighty years in Norway. The application of 100 per cent NPK + FYM for about twenty eight years increased WS-OC by about 32 to 41 per cent compared to the plots receiving only 100 per cent NPK (Singh *et al.*, 2003). The WS-OC represents less than one per cent of the total C in the soil. Liming had marked effect on this carbon fraction. Sousa and Melo (2003) revealed that water-soluble carbon reflects the initial stage of degradation of organic residues in the soil. Nitrogen fertilization at the rate of 120, 180 and 80 kg N ha^{-1} in the corn-corn cropping system increased water-soluble carbon content by about 15, 24 and 12 per cent, respectively (Yagi *et al.*, 2005). These workers, however, observed no effect of these N doses on WS-OC in soybean-corn sequence. Furthermore, the WS-OC was about 22 per cent less in the sub-surface as compared to the surface layers.

2.1.1.2.2 Water-soluble carbohydrates (WS-CHO): Carbohydrates are significant component of SOM, commonly accounting for 5-20 per cent of SOM and comprise 50-70 per cent of the dry weight of most plant tissues and hence, are the most abundant materials added to soil in the form of plant residues. Furthermore, carbohydrates are important constituents of soil microorganisms. They are considered to be the most readily available source of energy for organisms. They contribute to soil quality through their role in the formation and stabilization of soil structure (Cheshire, 1979). While much is known of the structure and function of carbohydrates in any organism, soil carbohydrates are

less well understood. Their study is important because of their role in soil structure following the demonstration that bacterial polysaccharides could cause aggregation of sand-clay mixtures (Martin, 1945). Oades (1967) reported that a soil under a four course rotation including pasture had nearly twice as high carbohydrate content as the same soil under a continuous wheat-fallow system. However, changes in carbohydrate content due to cropping system were not accompanied by significant changes in the proportion of organic matter present as carbohydrates. Singh and Singhal (1974) reported higher content of carbohydrate in surface soils of Mussorie hill, which decreased with depth. The soils developed under oak vegetation over shale parent material resemble podzolic soils with relatively high carbohydrate content. Total soil carbohydrate follow the same decreasing or increasing pattern as the organic matter content, being highest in organic rich surface horizons and lowest in soils low in organic matter (Schnitzer and Khan, 1978). The available data indicate that soil carbohydrate levels lie in the vicinity of one-tenth of organic matter content. Angers and N'Dayegamiye (1991) reported that bi-annual applications of 40 and 80 Mg ha^{-1} manure increased C and total carbohydrate contents of the whole soil and of all the particle-size fractions compared to the un-manured soils. Manure application at lower rates showed no effect on the composition of the carbohydrates. De Luca and Keeney (1993) observed significantly higher water-soluble carbohydrate content in prairie than in cultivated soils. Shepherd *et al.* (2001) observed significant decline in water-soluble and acid hydrolysable carbohydrates under medium and long-term cropping in coarse and fine textured mica and oxide rich soils. Saviozzi *et al.* (1999) compared the effect of sewage-

sludge and FYM on soil quality under field conditions for twelve years and observed that FYM treatments had higher amounts of total and water-soluble carbohydrates. However, both amendments were inadequate for the restoration of soil organic matter lost as a consequence of cultivation. Changes in the organic matter and carbohydrate contents of a silt loam were examined after ten years of applying solid cattle manure (Riffaldi *et al.*, 2003). Results indicated that continuous intensive cropping over the years significantly reduced acid hydrolysable carbohydrate carbon.

2.1.1.2.3 Water-soluble nutrients: Water-soluble nutrients, particularly N, P and S contribute more or less to the active pool of soil organic matter. Most of the work in general, has been carried out on the organic forms of these nutrients. Ammonical and nitrate forms of N contribute to the inorganic fractions of soil N. A negative N balance after sixteen years of fertilization was observed on poorly leached soils (Petrova and Gospodinov, 1986). These workers reported that the total N in the soil remained unchanged with slight increase in the hydrolysable fractions at high rates of N application while combined application of NPK at different rates changed the amounts of mineralizable and nitrate nitrogen. A significant improvement in NH_4^+ and NO_3^--N with the combined use of organic and inorganic N sources has been observed by a number of workers (Gupta and Narwal, 1988; Prasad *et al.*, 1996). Lime, FYM and P application over the years has been observed to have increased levels of total and hydrolysable nitrogen while continuous cropping declined the hydrolysable ammonium-N, amino acid-N and hexosamine-N contents (Kher and Minhas, 1992). Badiyala and Verma

(1990) reported highest content of inorganic N in FYM treated plots compared to rest of the treatments. Incorporation of lantana at increasing rates from 10-30 t ha^{-1} along with higher levels of N application increased all the hydrolysable-N fractions as well as organic carbon over the years (Sharma and Verma, 2001). Inorganic fraction of N decreases with the combined use of manures and fertilizers (Bhardwaj *et al.*, 1994b). Izaurralde *et al.* (1995) studied the effect of long-term and short-term agricultural practices on nitrate leaching in the cultivated soil and reported that plots receiving fertilizer N and manure contain 8 times more nitrate–N than other fertilized plots. Singh *et al.* (1999) reported that continuous use of N through organic and urea sources significantly increase the active pools of N along with the enhancement in its most reserve pools of hydrolysable ammonical N. In a long-term study under maize-wheat-cowpea cropping sequence, significant increase in mineralizable N in soil was reported (Sarwad *et al.*, 2001). However, comparatively lower amounts of these fractions were observed in plots receiving either 50 per cent NPK or 100 per cent NP or 100 per cent N alone.

Water-soluble P is normally reverted to an insoluble form, which is dependent on the concentration of Fe, Al and Ca present in the soil. Addition of chemical fertilizers over the years has significant effect on all P fractions. Phosphatic and nitrogenous fertilizers positively affect the inorganic P (including water-soluble P) fractions (McKenzie *et al.*, 1992 a, b). Long-term application of dairy manure at the rate of 20 t ha^{-1} per year increases soil P_i (inorganic P). Cumulative effect of manure and phosphatic fertilizers at normal rate has

resulted in an equilibrium between the addition and removal of inorganic P with the formation of less labile organic P in the soil (Zhang and Mackenzie, 1997). However, stable P fractions are not affected by fertilization and manuring (Tran and N'Dayegamiye, 1995). Verma (2002) reported a decline in water-soluble P fraction of inorganic P after twenty eight years in all the treatments under study over its initial status in an acid alfisol. The decline in water-soluble P, however, was less in FYM and lime treated plots as compared to rest of the treatments. Similar observations have been reported by number of other workers (Beck and Sanchez, 1994; Sharma *et al.*, 2002).

Williams and Steinbergs (1959) observed high correlation among all the S fractions. These fractions were, however, poorly correlated with S uptake and crop yield of oats. Freney and Stevenson (1966) have reported increase in the soluble sulphate upon liming. They attributed the same to the addition of sulphate with liming materials and its release from SOM by chemical hydrolysis at alkaline pH. Increase in fertilizer dose from 50 to 100 per cent NPK results in the increase in availability of S (Santhy and Channel, 1997). The P and S interaction is, however, synergistic at lower rates and antagonistic at higher levels of P. Similar findings have been reported by number of workers elsewhere in the country (Aulakh *et al.*, 1992; Sharma, 2002). Setia and Sharma (2004) studied the effect of continuous application of N, P and K on the chemical pools of sulphur in maize-wheat sequence for twenty two years and reported that application of increasing levels of P (upto 40 kg P_2O_5 ha^{-1}) significantly increased the water-soluble sulphur.

2.1.1.3 Slow Pool of Soil Organic Matter

Slow pool of soil organic matter occurs primarily with carbon soil bound aggregates. The soil aggregation is one of the important processes of stabilizing SOC pools. The physical protection of SOM within aggregates is important factor controlling decomposition of SOM in soil. The incorporation of SOM into aggregates limits the accessibility of substrate to microbes and fauna (Kooistra and van Noordwijk, 1996). Hence, characterization of water stable aggregate organic carbon (WSAC), also called slow fraction is important in maintenance of soil fertility. The sequestration of carbon in soil is not completely understood. The understanding of the issue requires quantitative information about the amounts of organic carbon in the various fractions and their rates of turnover.

Application of mineral fertilizers and animal manure increase the C and N content of whole soil, clay (<2μm) and silt (2–20μm) size fractions relative to un-manured samples, while the C content of the sand size fractions is less affected in a long-term experiment established in 1923. The sand, silt and clay fractions contained 10, 30 and 58 per cent of soil organic carbon, respectively (Christensen, 1987). Schulten and Leinweber (1991) observed that different fractions of soils and fertilization treatments tested for more than hundred years have distinct differences in carbon concentrations, its distribution and quality. Clay-associated C and N is high in the unfertilized treatment, whereas the application of farmyard manure preferentially increases soil organic matter associated with the fine and medium silt and thus, showing the importance of these constituents in assessing the positive effects of farmyard manure on soil

fertility. The various particle-size fractions and fertilizer treatments differ in the development of soil organic matter levels. Leinweber and Reuter (1992) reported that among the particle size fractions, the C concentrations were highest in the clay fraction and decrease in the order of medium silt, fine silt, coarse silt and sand while under the various fertilizer treatments, the concentrations were highest in compost followed by farmyard manure, straw + mineral fertilizer and mineral fertilizer, respectively. Singh and Singh (1996) quantified the distribution of soil organic carbon in different size fractions of water-stable aggregates and investigated the effect of residue (wheat straw) amendment under dry land cultivation. Organic carbon, associated with the macro- and micro-aggregates ranged from 6.52 to 29.56 and 4.99 to 22.11 g kg^{-1} soil, respectively. The application of wheat straw did not significantly influence the organic C levels, although the proportion of macro-aggregates increased, indicating thereby an improvement in soil structure. Gregorich *et al.* (1997) observed 2.5 times greater light fraction organic material in fertilized corn plots compared to non-fertilized plots.

Chenu *et al.* (1999) indicated strong decline in C content from 112 to 43 mg g^{-1} soil in less than 2 μm fractions with cultivation for seven to hundred years. The clay particles are less aggregated in the cultivated soils as compared to the forest soil. Gerzabek *et al.* (2001) evaluated the effect of organic fertilizer application and mineral fertilization on changes in organic carbon associated with different particle size fractions and indicated significant variation in these SOC fractions as a result of various treatments. Mass balance calculations showed that the proportion of organic carbon originating from organic amendments

decreased with particle size. However, the increase in organic carbon was about two fold over other treatments. Pillion *et al.* (2002) reported marked increase in mineral associated carbon pool in fallow-maize and lablab–maize cropping systems. The assessing effect of long-term cropping system on SOM and soil carbon changes is necessary to make projections regarding sequestration emission of CO_2 by agricultural soils.

The amounts of C in the Ap horizon after thirty nine years of continuous maize cropping were 9.5 and 14.0 per cent of the total organic C in unfertilized and NPK treated plots, respectively (Ludwig *et al.*, 2003). Fertilization did not affect the residence time of carbon in the soil. The Roth-C model suggested that 64 and 53 per cent of the organic C in the Ap horizon in unfertilized and fertilized plots, respectively is inert in nature. Carbon input and SOC sequestration, as governed by crop management strategies were assessed across 10 Mediterranean cropping systems. The observations indicated that C shifted from the 'less than 53-μm fraction' in low C input systems to the large and small macro-aggregates in high C input systems. A majority of the accumulation of SOC due to additional C inputs is preferentially sequestered in the micro-aggregates within small macro-aggregates. Hence, this micro-aggregate fraction is an ideal indicator for C sequestration potential in sustainable agro-ecosystems (Kong *et al.*, 2005).

2.1.1.4 Passive Pools of Soil Organic Matter (SOM)

Humification of organic matter, in general, proceeds in the soils which develop on base rich rocks resulting in the formation of humic acid (HA) type substances. Podzolic soils on the other hand, have fulvic acid (FA) type of humus

but almost similar in characteristics with HA (Kononova, 1966). Humic and fulvic acid bound nutrients are the important fractions of passive pool of nutrients and soil organic carbon whose improvement helps in nutrients restoration and their transformation in soil for high yields. He further concluded that the findings of some long-term experiments have shown a corresponding increase in the HA and FA content in manured plots.

Joshi and Saxena (1971) studied the distribution and nature of organic matter fractions in some soils of Rajasthan and found that HA fraction is less than FA in the humic substances of all the soils. Results from the long-term experiments covering various soil orders have brought out the fact that fulvic acid nutrients (FA-N, FA-P, FA-S) are higher than humic acid nutrients (HA-N, HA-P, HA-S) in all soils (Singh, 2002). Carbon contents in the HA fraction increase with variable N doses at all depths (Tan *et al.*, 1972). Dhir (1973) reported predominance of FA in humus in some soils of high altitude.

A study with regard to distribution and nature of organic matter made by Adityachaudhary and Saha (1973) on the rice growing soils of West Bengal indicated that humic acid occurring in the bottom layers is more aromatized in nature than the top layers. Further, Banerjee and Chakraborty (1977) under similar set of conditions in surface soils observed that moderate moisture regime; slightly acidic to neutral soil reaction and fairly intense microbiological activity are the main factors of HA formation while reverse of these favoured the formation of FA. In a long-term fertilizer experiment for twenty years, overall humus losses in 0-20 cm soil depth account for 0.06-0.2 per cent of C. But, application of

inorganic fertilizers plus FYM is not accompanied by humus loss. In lower horizons, systematic fertilization increases humus content by 0.25-0.54 per cent and resulted in sharp decline in FA fractions (Stulin and Zolotareva, 1988). Application of FYM either alone or in combination with fertilizers and/or lime in a Paleustalf, enriched the soils with total organic carbon and humic fractions (Sharma *et al.*, 1988). Fertilizer use alone for more than nineteen years, however, gradually declines HA fractions. The data pertaining to the elemental composition of humic and fulvic acids show that HA contains more carbon than FA (Sarmah and Bordolai, 1993).

Humus conservation in soils is favourably influenced by N fertilization through maintenance of equilibrium between humification and mineralization processes where organo-mineral fertilization of cultivated soils increases the fertility by accumulation of organic matter (Tianu, 1997). Application of high levels of N fertilizers to maize, wheat and pea crops increased the ratio of low molecular weight humus compounds which have significant role in the fixation of toxic materials and adsorption of plant protection chemicals (Balane and Daniel, 1997). Wang and Zhang (1998) observed an appreciable increase in SOM with the application of organic materials viz; compost and maize straw resulting in the increased pigment ratio (E_4:E_6) of humic acid after seventeen years of field experimentation.

The concentration of humic and fulvic acids increases substantially with the graded doses of mineral fertilizers. The concentration of humic acid, however, was less than fulvic acid regardless of the treatments (Santhy *et al.*, 1997). Application of 40 m^3 compost either alone or in combination with mineral

fertilizers for about eleven years resulted in significant increase in carbon content of all organic matter fractions (Rosales *et al.*, 1999). Further, the application of compost with mineral fertilizers supplies greater amounts of passive pools of SOC to the surface layer.

The fulvic acid is more acidic than humic acid due to high content of carboxyl group (Ram, 2001). Results of long-term fertilized soils have indicated that frequent increase in SOM contents could be attributed to resistance of HA fractions to microbial degradation (Filip and Kubat, 2001). Long-term application of organic fertilizers for considerable time results in increase of total humus and humic acid content and décline in fulvic acid while the use of mineral fertilizers alone results in decline of fulvic acid content in the humus (Filon and Shelar, 2002). Yagi *et al.* (2003) observed that carbon-humin fraction represents about 58 per cent of SOM, while HA-C fraction showed predominance over the FA-C fraction. These workers showed a decline in the C-humic acids with the use of vermi-compost. Lime application, however, showed no effect on total organic matter. Doane *et al.* (2003) reported 5-9 per cent C turnover or accumulation in FA fraction and 16 per cent in the HA fraction in agricultural systems. Zhang and He (2004) reported improvement in the quality of SOM, characterized by HA and FA ratio of 0.8 in the first fifteen years with gradual increase in the subsequent years in a long-term field experiment. Walker *et al.* (2004) revealed that high altitude and high rainfall soils have large accumulation of humin and fulvic acid as compared to humic acid. They also observed marked decline in soil humus fractions with increasing depth irrespective of the treatments and agro-climatic conditions. Yagi *et al.* (2005) reported 17 and 30 per cent less FA-C and HA-C, respectively in the 20 to 40 cm soil layer as compared to surface layer.

2.1.1.5 Passive Pools of Nutrients (N, P and S)

The major portion of N in the soils comprises humic acid and humin fractions and only a small amount (6.5 % of the total N) was in the fulvic acid fractions (Sowden *et al.*, 1976). Kamat *et al.* (1982) reported that higher doses of FYM markedly increase all forms of N but reduce the content of insoluble humin N indicating low mineralization of resistant plant material. Theoretical structures of humic acid molecules don't include phosphorus (Felbeck, 1965). Organically bound sulphur is the predominant form of S and inorganic forms account for only few per cent of total S in soil. Although there is considerable information on the forms of soil organic S, few attempts have been made to investigate their fractions in the passive pool of soil organic matter. McLaren and Swift (1977) indicated that FA fraction contributes only 15 per cent of the mineralized S and the sizeable proportion of S mineralization was derived from humic and fulvic acid and residual humin fraction of SOM pool. Results of various long-term fertilizer experiments in India have indicated the significant positive effect of balanced and integrated use of organics and inorganics on all passive pools of N, P and S (Singh *et al.*, 2003).

2.1.2 Microbial Environment of Soils

Microbial transformations play a pivotal role in nutrients cycling via decomposition, immobilization and mineralization. Therefore, quantification of major nutrients viz; N, P and S held within the microbial biomass becomes essential. Such information is necessary in estimating plant availability of nutrients in soil and for the development of appropriate models (Wu *et al.*, 1994).

2.1.2.1 Soil Microbial Biomass (SMB-C, SMB-N, SMB-P and SMB-S)

The amount of microbial biomass although comprise a small portion of SOM, yet reflects the total organic matter content within the living microbial component. The total amount of microbial C and N in soil is generally greater in soils of cooler and wetter regions compared to warmer and drier regions (Allison, 1973; Spain *et al.*, 1983). Sridevi *et al.* (2003) reported that C mineralization and microbial biomass dynamics in soil ammended with residues are strongly controlled by the proportions of soluble and fibre fractions and the N concentration of the residues. Microbial biomass comprises 2-3 per cent of soil carbon and 3-5 per cent of soil N (Jenkinson and Ladd, 1981). It acts as a catalyst for the conversion of plant nutrients from stable organic forms to available mineral forms over longer periods (Coleman *et al.*, 1983). Being a labile fraction of SOM, microbial biomass can be a useful early indicator of soil quality and can reflect organic matter changes and soil development (Mulongoy and Mercx, 1991).

Brookes (1995) agreed on the use of microbial biomass C as indicator of soil quality owing to its high sensitivity to changes in land use and management practices. Ladd *et al.* (1994) added that microbial biomass C is a good measure of the state of the edaphic environment and its inclusion in a soil quality index lead to reduction in the number of properties that need to be considered. Thus, soil microbial biomass influences crop productivity besides nutrients cycling.

Soil and crop management practices can greatly influence soil biological activity through their effects on the quantity and quality of organic matter added to the soil and the initial distribution of such material in the soil. Thus, soil systems with the highest organic matter input also tend to have the greatest microbial biomass and activity (Sparling, 1985). Application of fertilizers in combination with manures over the years contributed about 56 percent of biomass carbon to the soil under soybean-wheat cropping system (Prakash *et al.,* 2002). Spring barley straw burned or incorporated in the soil for eighteen years (Powlson *et al.,* 1987) increased total soil organic C by 5 per cent, and total soil N by about 10 per cent. Addition of organic manure in the soil showed a higher organic N and biomass N content compared to rest of the treatments under long-term fertilization on continuous maize (Balik *et al.*, 1999). Application of 144 kg N ha^{-1} for 135 years increased total soil N and mineralization rate of biomass, but had no effect on microbial biomass N and C (Glendining *et al.*, 1996). However, microbial biomass C increased by about 45 per cent, an easily measurable change. Management of soils that leaves residue on the soil surface often results in higher concentrations of soluble organic carbon compounds (Alvarez *et al.*, 1998), which result in the enhancement of microbial properties.

Phosphorus is the second major nutrient in practical agriculture; being fairly immobile, becomes unavailable for plant uptake through fixation into insoluble form. Under such circumstances, microbial biomass although relatively small, can be an important source of P for microorganisms.

Anderson and Domsch (1978) reported that SMB-P in the upper 12.5 cm of 26 agricultural soils ranged from 1.7 to 2.4 kg P ha^{-1}. Jenkinson and Ladd (1981) have reported 11 kg ha^{-1} biomass P in an un-manured soil under continuous wheat for about 140 years. Chauhan *et al.* (1981) found that the microbial biomass in soils range from 100 to 500 µg g^{-1} soil. Hence, in P deficient soils of the world, P release during mineralization of the microbial biomass could have significant contribution to P nutrition of arable corps (Banger *et al.*, 1990).

Organic S compounds are unavailanle to plants and require their conversion to inorganic sulphate before their uptake by plants for which role of enzymes and microorganisms is of great importance (Castellano and Dick, 1991). Although microbial biomass contains only about 2 per cent of the total S, this fraction is considered to be extremely labile and may hold the key to understand the S turnover in soils (Biederbeck, 1978). Very little information, however, is available on turnover of SMB-S and its flux through microbial biomass in soil system.

The supply and availability of additional mineralisable and readily hydrolysable C due to manure application characteristically results in increased biomass, activity and abundance of soil microbes in a soil system (McGill *et al.*, 1986; Ocio *et al.*, 1991). Many other studies, conducted under both tropical and temperate conditions, have also shown significant build up in microbial biomass C, N and P in soils receiving manure (Hasebe *et al.*, 1985; McGill *et al.*, 1986; Collins *et al.*, 1992; Goyal *et al.*, 1992). Hasebe *et al.* (1985) and Ritz *et al.* (1997) have also observed greater microbial biomass C in soils treated with

organic manure than with inorganic fertilizers or no-fertilizer treatment. In the Northern Guinea savanna zone of Nigeria, microbial biomass C of a Typic Haplustalf manured for forty five years with cow dung increased by 76 per cent over the un-manured control (Goladi and Agbenin, 1997). Seasonal changes in carbon availability and microbial biomass have been studied in soil under an irrigated wheat-maize cropping system receiving different fertilizer treatments for more than ten years (Mahmood *et al.*, 1997). They reported that microbial biomass carbon decreases in urea-treated plots but increase slightly at the higher rate of FYM. Highest microbial biomass turnover rate takes place at higher rate of FYM followed by its lower rates and urea treatments. Soils receiving the application of FYM either alone or in combination with inorganics and P fertilizer result in highest amount of microbial biomass C and P whereas application of ammonium sulphate decreases their respective contents (He *et al.*, 1997). Bucher (1999) reported significant increase in soil microbial biomass C (SMB-C) with manure addition as compared to industrial fertilizer addition on Pennsylvania farms that had different soil management histories.

Reports on the effects of inorganic NPK fertilizers on soil microbial biomass and numbers are inconsistent. In the long-term experiment in Saskatchewan, significant increases in soil microbial biomass due to fertilization have been reported (Biederbeck *et al.*, 1984). Similar response to continuous applications of NPK fertilizers has been observed in a number of studies in India (Goyal *et al.*, 1992) and Japan (Kanazawa *et al.*, 1988). The increase in microbial biomass is attributed to improvement in soil fertility and the associated

enhancement in plant growth and higher rhizodeposition. Sharma *et al.* (2002) have reported significantly higher amount of microbial biomass in plots receiving FYM for the last thirty years compared to the control plots. There is, however, statistically no difference in microbial biomass in the plots receiving manure and mineral fertilizers.

McGill *et al.* (1986) while studying the dynamics of soil microbial biomass C and N in the long-term Breton Plots, however, have observed decrease in microbial biomass due to NPK application. The lack of response or decrease in microbial biomass and activity is attributed to the acidifying effects of the fertilizers and the resultant impairment of the survival capacity of many of the soil microorganisms (Domsch, 1986). A parallel study conducted on long term experimental plots at Saskatchewan (Canada) revealed that the amount of soil microbial biomass C is almost the same in unfertilized control and the plots receiving NPK fertilizers (Campbell *et al.*, 1991). The results of experiments conducted for more than ten years at two sites in Kansas have also shown that the contents of soil microbial biomass C and N in plots fertilized with 224 kg N ha^{-1} yr^{-1} are significantly lower than that of the unfertilized control plot (Omay *et al.*, 1997). Liebig *et al.* (2002) observed significantly higher microbial biomass C and N content in zero and low rate N treatments as compared with high rate N treatments.

Information on the impact of NPK fertilizers on soil microbial biomass and numbers, besides being conflicting is also very limited and more research in this regard is needed.

Soil microbial biomass, in general, increases with the root growth and rooting density of the crop (Lynch and Panting, 1980). The fine textured clay soils tend to have more microbial biomass. In addition, the microbial fraction in clay soils tends to comprise a greater portion of total organic carbon because of the protective effect of clay on the microbial biomass (Van Veen *et al.*, 1985; Merckx *et al.*, 1985). Smith and Doran (1996) have revealed that high soil bulk density caused by soil compaction could lead to low aeration and root growth with subsequent low microbial growth.

Negative effects of acidification on microbial biomass have been observed by some workers (Kowalenko, 1978). High level of inorganic nutrients and low pH of fertilized plots interferes with biological assays to estimate microbial biomass (Widmer *et al.*, 1989; Amato and Ladd, 1994). Long-term fertilizer use though improves soil nutrients status, leads to soil acidification and might decrease the microbial biomass while still improving crop yield (Ladd *et al.*, 1994). On the contrary, soil microbial biomass C and N has been reported to be significantly high in productive acid soils of Kenya's central highlands (Murage *et al.*, 2000).

2.1.2.2 Microbial Count

The chemical factors play crucial role in the survival of microorganisms in ecologically different niches of soil (Chapman, 1965). Fungi are dominant in acidic soils while bacteria and actinomycetes show their abundance in neutral or alkaline soils (Alexander, 1977). The bacterial and actinomycetes population is high in plots receiving manure than the un-manured plots (Martyniuk and Wagner, 1978).

In strongly acidic soils, liming plays a crucial role in increasing the bacterial population (Shah *et al.*, 1990). Deb (1990) observed reduction in fungal population and increase in the actinomycetes and bacterial population with the application of mineral fertilizers. Zang and Zak (1998) on the other hand, observed no effect of N on the microbial population while Pankhurst *et al.* (1995) reported significant effect of N-fertilization on micorrhizal fungi, protozoa and cellulose decomposition.

The soil P status plays a significant role in influencing the microbial growth. Microbial biomass and their count increase with increasing application of FYM and both the parameters are more in treatments receiving inorganic N along with FYM over a period of time due to better root growth (Kukreja *et al.*, 1991; Goyal *et al.*, 1992; Sriramachandrasekhran *et al.*, 1995). The bacteria and actinomycetes have significantly positive relationship with crop yield and available nutrient status in the plots receiving organic and inorganic fertilizers while fungal growth is negatively correlated to FYM addition. Malewar *et al.* (1999) observed higher microbial growth in the treatments receiving organic and inorganic fertilizers under sorghum-wheat cropping sequence.

2.1.3 Carbon Sequestration and SOM Dynamics

Central to the carbon cycling processes in soils, is the dynamics of soil microbial population, the complex physical, chemical composition of SOC and the associated nutrients, as well as the various degrees of physical and chemical protection afforded to the SOC and associated nutrient elements in the soil. Soil organic matter dynamics are fundamental soil biological processes, which govern

soil nutrient cycling. Soil conditions particularly temperature, moisture, texture and structure, tillage and cropping management, all have important impact on carbon dynamics (Li and Feng, 2004). The gross turnover time of SOC expressed as ratio between total amount of organic carbon in the soil at steady state and the annual rate of addition could be more than twenty years in temperate regions (Stout *et al.*, 1981). Organic carbon stabilized in the soil would remain for a great length of time, resulting in a large fraction of very old, stable organic carbon in the soil. In order to be considered as an effective option to counter global green house effects, management practices aimed at carbon sequestration in soils must lead to long-term increase in SOC. Research on SOM dynamics has advanced many decades. A wide range of agricultural practices exists for sequestering organic carbon in agricultural soils. Among these, application of organic material inputs is one of the most common used management practices. Data on SOC (Jenkinson and Rayner, 1977) and model prediction (Feng and Li, 2002) illustrated that SOC increased with animal manure application in Rothamsted (U.K.) for 125 years showing that steady state is not reached even after such long period and is not expected to be reached for further hundred years. These results suggest that continued input of carbon is essential to maintain high SOC level. However, inorganic fertilization alone showed negligible changes in SOC in the same experimental set up. Experiments are being conducted at CAZRI to study the possibility of C-sequestration in pearl millet based production systems (Praven Kumar *et al.*, 2001). Results of these experiments suggested that annual application of 2.5 tonnes manure with 40 kg

N ha^{-1} stabilized grain and total biomass of pearl millet which was statistically at par with 5 tonnes manure along with 40 kg N ha^{-1} and also showed a net C-sequestration. Recently, SOC dynamics and changes in C sequestration have been well described through various organic models (Roth-C, CENTURY, K-model etc.) This part is further discussed in detail under "Validation of C models". Soils initially low in SOC tend to show much greater gains in SOC compared to soils initially high in carbon. Bremer *et al.* (2002), on the basis of preliminary evidences suggested that under improved management practices, dark brown soils could increase SOC by 8 to 10 t ha^{-1} over the next two decades. Similar carbon storage opportunities exist for the thin black and gray Luvisols. However, soils in the sub-humid regions rich in SOC show less potential for C-sequestration. After the implementation of improved management systems, it takes approximately fifteen to twenty five years before the soil carbon sink becomes saturated and additional carbon cannot be sequestrated (Cole *et al.*, 1996). High addition rates of carbon via organic matter and nutrients compared to its aerobic decomposition result in the carbon sequestration over time (Golchin *et al.*, 1995; Kay, 1998). Hence, it may take four years or more in soils high in carbon to detect changes in SOC.

2.2 Relationship between SOM Pool, Crop Productivity and Nutrients' Supply

The application of manures and fertilizers significantly increase soil nutrient levels (N'Dayegamiye, 1990) and crop response to mineral fertilizers decrease in subsequent years (N'Dayegamiye, 1996). The application of manure for thirty six years have improved the nitrogen and phosphorus supplying power

of Chernozemic clay soil and subsequently improved the wheat productivity (Campbell *et al.*, 1986). Application of P fertilizers and dairy cattle manure also increase available P forms in soil (McKenzie *et al.*, 1992 a, b; Tran and N'Dayegamiye, 1995). The studies conducted by McGill *et al.* (1986); Insam *et al.* (1991); Goyal *et al.* (1992) have revealed positive relationship of crop yields with soil microbial biomass N and P. Howard and Howard (1990) have found structural destabilization and reduction in crop yield in soils with carbon content less than their threshold value of 2 per cent. While studying the relationship between SOC in the surface soil and soil productivity, Janzen *et al.* (1992) reported no further increase in the productivity beyond an upper threshold level of soil carbon content. Consistent increase in crop and sugar beet yields in sandy soils resulted in about 0.7 to 0.9 per cent increase in SOC over six years (Johnston, 1991). Accumulation of higher carbon and N content due to green manure addition resulted in high crop productivity and returned the plant input after thirty years of continuous cropping in Sweden (Paustian *et al.*, 1992). Wheat yields get reduced as a result of high soil nitrogen levels from manure and nitrogen fertilizer (Bulman and Smith, 1993). Raupp (1999) observed that yields of some crops like spring wheat, winter rye and potatoes showed no relationship to the SOM content of soils. This is, however, in contradiction to the findings emerged from other trials under similar site conditions in which high crop productivity was recorded in plots with high SOM content. The soil organic matter plays significant role in improving upon the crop productivity in dry areas as was evident from about 10 t ha^{-1} more decline in crop yields under control than in the

manurial treatments. It is virtually impossible to obtain potential yields with SOC content below 1 per cent (Kay and Angers, 1999). Suresh *et al.* (1999) have also reported significant positive relationship between soil organic carbon and crop yields over the years. The plant-soil system with manure fertilization seems to compensate for poor environmental conditions.

Microorganisms make up only 1 to 8 per cent of the soil organic mass, but they have a great influence on crop production by dominating decomposition through bio-transformations (Roder *et al.*, 1988). A positive correlation exists between their amount and crop productivity. Vance *et al.* (1987) observed a close linear relationship between biomass carbon and SOC with the regression accounting for 98.6 per cent of the variance in the data. Microbial biomass carbon and phosphorus were significantly correlated ($r = 0.88$, $p<0.05$) for six tropical soils (Srivastva and Singh, 1991). Soil organic carbon has significant positive relationship with bacteria ($r = 0.75^{**}$), fungi ($r = 0.89^{**}$) and actinomycetes in FYM treated plots (Sriramachandrasekhran *et al.*, 1995). Microbial biomass N ($r = 0.98$) and P ($r = 0.80$) correlated significantly with microbial biomass carbon in a long-term experiment (Manna *et al.*, 1996). Soil organic carbon also shows a positive correlation with biomass C ($r = 0.66$, $p<0.01$) and is attributed to the application of FYM, which supports the development of microbial biomass during entire growing period of crops. The P uptake in the pasture is well correlated with the sum of P in biomass and soil available pools (He *et al.*, 1997). Patil and Varade (1998) have reported a positive correlation of bacteria and actinomycetes with available nutrients status

under organic treatments whereas fungi showed a negative correlation under inorganic treatments. Santhy *et al.* (1999) observed higher correlation between organic carbon and biomass carbon (r = 0.845**) in an inceptisol. Further, biomass accorded for 78 per cent variability in biomass N under long-term cropping and manuring programme.

2.3 Validation of Carbon Models

Soil organic matter modeling, arguably once an obscure discipline, is gaining recognition as a key part of efforts to better understand and manage the terrestrial carbon cycle. Soil organic carbon models are being called upon to guide policy and decision making at local, national and international levels. This increased recognition brings with it major challenges as well as opportunities for our science. The current paradigm, related to the basic concepts used in most SOM models - multiple functional pools, first-order kinetics, climatic and edaphic-driven rate reduction factors has been established since late 1970's. Refinements in the capabilities of SOM models have continued over time, and in recent years, have been aided by increased communication between different modelers, by the collation of existing long-term field experiments and the widespread use of isotopic techniques. Existing models have been successful in providing research direction, interpreting field experimental results and are beginning to be used to address policy issues relating to soil C dynamics (Paustian and Paul, 1999).

Despite this continuing progress, new approaches to modeling SOM are being pursued and deficiencies in our understanding and prediction of SOM behavior are widely recognized. Considerable debate has centered on the

fundamental problem of better reconciling experimental vs theoretical descriptions of SOM composition and whether "modeling the measurable" or "measuring the modelable" offers the most fruitful approach.

New developments in SOM modeling are considering processes and phenomena spanning a wide range of scale. At the micro scale, the interaction of different fractions of SOM and soil physico-chemical properties is being explored. Factors determining the capacity of soils to stabilize organic matter and the influence of management practices on SOM turnover are issues at the field scale. At regional and global scales, modeling SOM is being linked to land use and climate changes and the economic and social systems that drive these changes. Further, progress in modeling SOM dynamics, across a range of scales, presents major challenges as well as opportunities to provide society with better decision making capabilities. The potential long-term changes in SOC resulting from changing management can be evaluated only with the aid of the models of SOC dynamics. Reporting of carbon sequestration for individual producers and farmers require reliable tools to evaluate changes in soil organic carbon. Two options are available to this purpose; direct experimental measurement and monitoring, and predictions with soil organic carbon models. To be of practical value to the producers and farmers, these changes need to be evaluated over relatively short periods, from a few years to a decade. Change of soil organic carbon, however, is slow and occurs over much longer time periods. Direct measurement and monitoring of soil organic carbon changes over short periods must deal with uncertainties of sampling and measurement errors, and

more importantly, uncertainties resulting from non-uniformity of field soils. Prediction based on models validated against available experimental evidence is another option. For this purpose, the model must be easy to use, based on sound theoretical description of soil organic carbon processes, and contains only parameters that are physically meaningful and experimentally measurable. The models must also be able to reproduce both the quick decomposition of plant residues within a single season and the exceedingly great age of organic carbon in soils in order to be considered valid for predictions in both the short term changes in soil organic carbon, that is, a few years to decades, and for predictions in much longer term stabilization of soil organic carbon.

A large number of soil organic carbon models have been developed in the past (Hunt 1977; Jenkinson and Rayner, 1977; McGill *et al.*, 1981; Molina *et al.*, 1983; Van Veen *et al.*, 1984; Andren and Paustian, 1987; Jenkinson *et al.*, 1987; Parton *et al.*, 1987; Jenkinson,1990; Smith *et al.*, 1997). An example is Roth-C model (Coleman and Jenkinson, 1996) where soil organic carbon is divided into decomposable and resistant plant materials and active biomass and physically and chemically protected soil organic matter compartments. The rate constants used to describe these compartments range from 4.2 per year for decomposable plant material to 3.5×10^{-4} per year for resistant soil organic matter (Li and Feng, 2004). Smith *et al.* (1997) conducted an extensive comparison of various compartment models available at the time for predicting changes in long-term soil organic carbon dynamics.

2.3.1 Roth-C Model

Roth-C-26.3 model (Jenkinson and Rayner, 1977; Coleman and Jenkinson, 1996) is one of the earlier computer based models to predict the turn-over of organic carbon in soil. It is solely concerned with soil processes, and does not contain a sub-model for plant production, and does not attempt to calculate annual returns of plant C to the soil from above-ground yields. Turnover of carbon is sensitive to soil type, temperature, moisture, and plant cover. Nitrogen and carbon dynamics are not interconnected, the inert organic matter compartment is initialized using carbon-dating, and starting values are obtained by running the model to steady state. It uses primarily monthly data, and shares several basic concepts with CENTURY model. Roth-C-26.3 operates in two modes. If the organic carbon inputs are known, it can be run in 'forward mode' to calculate how this input will decay in a particular soil under a particular climate, and how this influences soil organic carbon. However, generally, these organic carbon inputs (i.e. from litter decay, root death, root exudation, turnover of microbial biomass, etc.) are not accurately known, and the model can, therefore, be run in 'reverse' mode to calculate what these inputs must be in order to match an observed change in soil organic carbon levels.

It has been widely used to simulate changes in SOC content on variety of soil types (Jenkinson *et al.*, 1987) and for variety of land uses including arable land, grassland and forestry (Coleman *et al.*, 1997). It has been used at the regional scale (Parshotam *et al.*, 1995) and at the global scale (Post *et al.*, 1982; Jenkinson *et al.*, 1992; Polglase and Wang, 1992) to estimate either net primary productivity or CO_2 fluxes. Roth-C is applicable to freely drained mineral soils, and not to permanently waterlogged or organic soils.

Coleman *et al.* (1997) described the testing of Roth-C-26.3 against 18 long-term soil organic carbon data sets. There is acceptable agreement between observed and predicted data for 14 of the data sets. Skjemstad and Janik (1996) predicted the changes in total organic carbon with time at 20 long-term sites varying in soil type, climate and management by using Roth-C model. The model was run for the duration ranging from 11 to 73 years. The predicted vs measured results showed reasonable agreement for the 0-10 cm soil horizon. A recent comparison of leading SOC models showed Roth-C to be among the six with the best performance in simulating long-term trends in SOC across a range of land uses, soil types and climatic regions (Smith *et al.*, 1997). Grant *et al.* (2001) compared model output for changes in soil C with those measured in a Gray Luvisol (Typic Cryoboralf) at Breton (Alberta), during 70 years of a 2-year wheat (*Triticum aestivum* L.) – fallow rotation with a 5-year wheat – oat (*Avena sativa* L.) – barley (*Hordeum vulgare* L.) – forage – forage rotation with un-amended, fertilized and manured treatments. Consequent changes of soil C in the model were corroborated by declines of 14 and 7 g C m^{-2} yr^{-1} measured in the control and fertilized treatments of the 2-year rotation; by gains of 7 g C m^{-2} yr^{-1} measured in the manured treatment of the 2-year rotation; and 4, 14, and 28 g C m^{-2} yr^{-1} in the control, fertilized and manured plots of the 5-year rotation. Model results indicated that soil C below 0.15 m declined in all treatments of both rotations. Simulations were made of changes in SOC over 140 years using Roth-C model under three fertilizer N regimes to examine the effects of changes in fertilizer N use on SOC in arable soils in England and Wales (Webb *et al.*, 2003).

Results indicated a negligible impact on SOC in arable soils over the next 140 years by decreasing annual fertilizer N use to 50 or 100 kg ha^{-1} less than currently applied to cereals. Soils with more than 180 g kg^{-1} clay and 16 to 27 g kg^{-1} SOC at the beginning of the model runs were predicted to have about 21 to 23 g kg^{-1} SOC after 140 years, while soils with less than 180 g kg^{-1} clay and about 12 g kg^{-1} SOC would change little over 140 years. Roth-C model predicted about 54 per cent increase in the SOC stock in 100 years after conversion of forest land to pastures (Cerri *et al.*, 2003). Paul and Polglase (2004), in an attempt to calibrate the Roth-C sub-model within FullCAM (Full Carbon Model) framework of models, observed that calibration of Roth-C was most sensitive to the partitioning of carbon during decomposition of debris between that lost as CO_2 and that transferred to soil. The dynamics of SOC in the upper 22 cm of arable land were modeled for a soil association with low and high initial carbon stock. The plant input of 2.5 t C ha^{-1} calibrated for the long term in Gembloux was used (Wesemael *et al.*, 2004). These workers observed that starting from 1960 SOC values; the Roth-C model generally predicts the observed values in 1990 reasonably well as model prediction passes nearly through the confidence limits of the observations. They also calibrated the model on Belgian long-term experiments and model reasonably represented the observed SOC stocks with uncertainties ranging from 5.8 per cent root mean square error (RMSE) for the control to 9.5 per cent for the FYM treatment. Falloon and Smith (2003) also reported almost similar results for the RMSE for long-term experiments in UK, Hungary and Sweden. Skjemstad *et al.* (2004) for the first time demonstrated a

methodology linking measured soil carbon pools with a conceptual soil carbon turnover model. They observed that modeled and measured data of SOM fractions viz; particulate organic carbon and humic pool were in agreement for two long-term rotation trials upto 30 cm soil depth. It is suggested that physically isolated fractions might be more useful in this regard than the more classical chemical approaches (Cambardella, 1998; Sohi *et al.*, 2001). Simulations made by SUNDIAL Rothamsted model suggested more decline in SOM in fertilized plots as compared to the control plots (Sirotenko *et al.*, 2002). These findings are contradictory to those emanating from other long-term experiments in the west (Glendining and Powlson, 1995).

2.3.2 Carbon and Nitrogen Dynamics (CANDY) Model

Carbon and Nitrogen Dynamics (CANDY) is a modular system containing different sub-models and a database system for model parameters, measurement values, initial values, weather data, and soil management data. The model is based on long-term experiments at Bad Lauchstädt in Germany, and is used for simulating the short-term dynamics of nitrogen transformation and the long-term dynamics of carbon sequestration in arable soils (Franko and Oelschlaegal, 1995), and further validation on a number of long-term data sets is given by Franko and Komarov (1997). Use of the model for long-term simulations is in two parts. The basic model operates on a daily time step and calculates a measure of the turnover activity, or 'biological active time' (BAT), and the flux of carbon from fresh OM to SOM, termed 'reproducing carbon'. Organic matter inputs to the soil are provided as inputs to the model, with different types (e.g.

straw, slurry, manure, compost) being accommodated. Inputs from crop residues are calculated from crop yields by linear regressions. The daily model requires a detailed soil description, daily weather data (solar radiation, air temperature and rainfall), crop yields, and an initial value for the decomposable carbon pool. A second simpler model, operating on an annual time step, and implemented in an Excel spreadsheet, uses the BAT and the annual flux of reproducing carbon calculated with the daily model. Nitrogen fluxes are not simulated. This model also requires an initial value for the decomposable carbon pool. The goal-seeking facility of the spreadsheet can be used for parameter estimation.

The CANDY-model has been evaluated on a wide scale of long-term experiments (Franko and Schenk, 1999). It has been integrated in a Geographic Information System in order to investigate matter fluxes in agro-ecosystems on a regional scale. Required inputs are soil parameters, weather data and management information. A special map and a linked database represent each of these information pools. For this investigation, management information since 1980 was used to model the carbon dynamics for an area of about 4,000 ha. Results showed a continuous increase of soil organic matter with fluctuations because of precipitation differences. The system is going into the range of optimal soil organic matter content leaving only little capacity for further increase of carbon storage in soil.

Both models require an estimate of inert carbon, which can be either estimated by optimization or obtained from experimental measurements.

Materials and Methods

Chapter III

MATERIALS AND METHODS

A field experiment entitled, *"Carbon sequestration and nutrient dynamics in a long-term lantana amended soil under rice-wheat system"* was carried out in on going long - term experiment with rice (*Oryza sativa*) - wheat (*Triticum aestivum L.*) cropping system at the experimental farm, Department of Soil Science, Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya, Palampur.

The details of the materials used and methodology adopted during the course of investigation have been described under the following heads:

3.1 General Description of the Study Area

3.2 Field Studies

3.3 Laboratory Studies

3.4 Validation of Carbon Models

3.5 Statistical Analysis

3.1 General Description of the Study Area

3.1.1 Location

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 the Palam valley of Kangra district at the foothills of *Dhauladhar* ranges and is characterized as mid hill sub-humid zone of Himachal Pradesh.

3.1.2 Climate and Weather Conditions

The climate of the experimental area is characterized as wet temperate with mild summers (March to June) and cool winters (December to February). The mean monthly rainfall, temperature, and total yearly rainfall patterns for the period 1988 to 2005 are presented in figures 3.1 and 3.2 and appended in Appendices I and II, respectively. The data on mean monthly evaporation modified as per the method of Muller (1982) is given in Appendix I. The area received 2007.0 mm mean annual rainfall (averaged for 1988 to 2005) with mid June to mid September being the wettest months. The mean minimum temperature during 1988 to 2005 was 5.2°C in January and the maximum 30.2°C in May.

3.1.3 Soils

Taxonomically, the soils of the study area falls in the order 'Alfisol' and sub-group 'Typic Hapludalf' (Verma, 1979). In the genetic system of classification, the soils of the area has been classified as "Grey Brown Podzols" and have developed from fluvioglacial parent material. These soils owe their origin to rocks like slates, phyllites, quartzites, schists and gneisses. The soils are acidic in reaction (pH 5.2 to 6.2). Some important physico-chemical characteristics of the surface soil (0-0.15 m) of the experiment before *kharif* 1988 are given in Table 3.1.

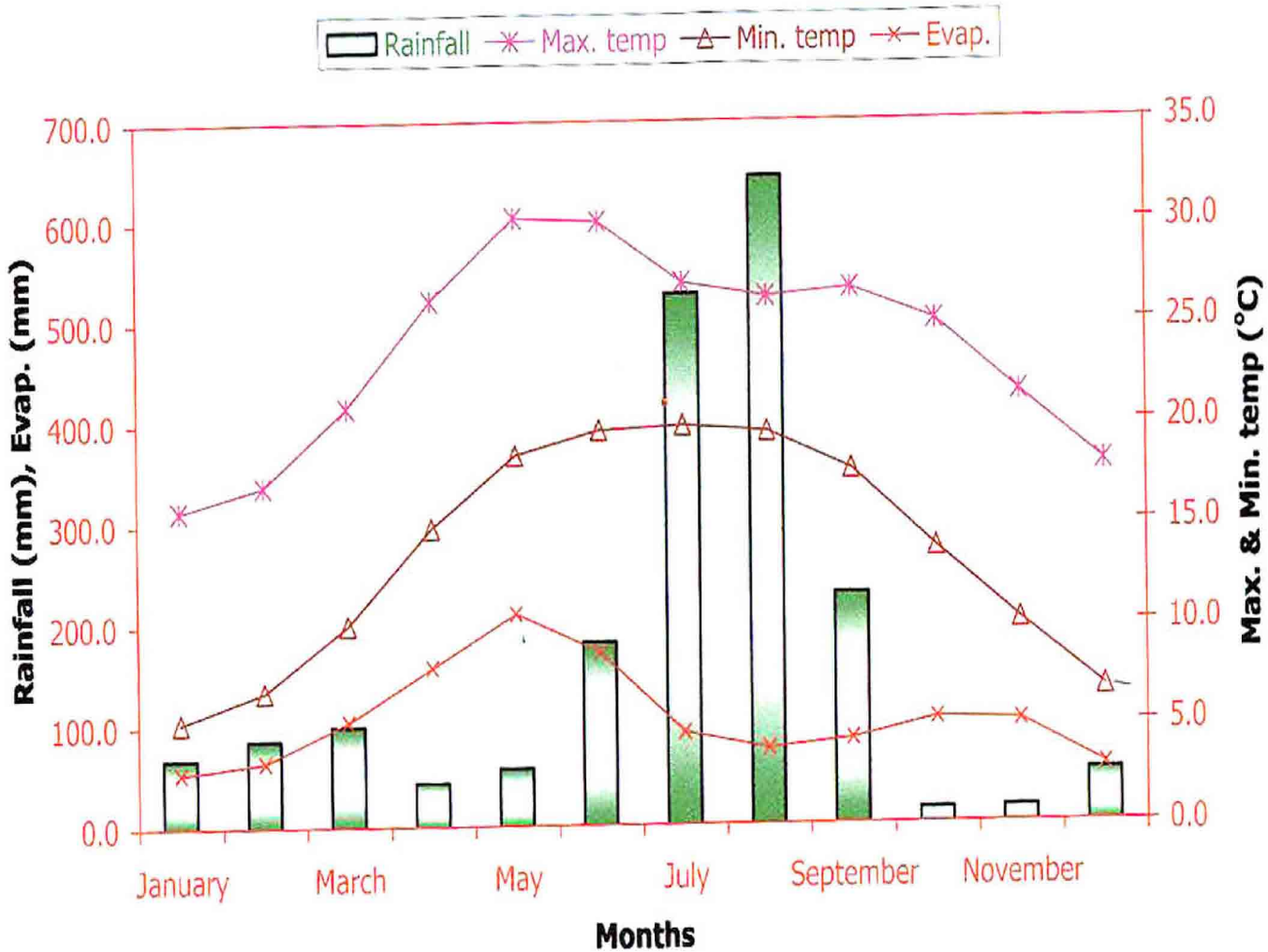


Fig. 3.1 Mean monthly rainfall (mm) and air temperature (°C) at Palampur (HP) for the period 1988 to 2005

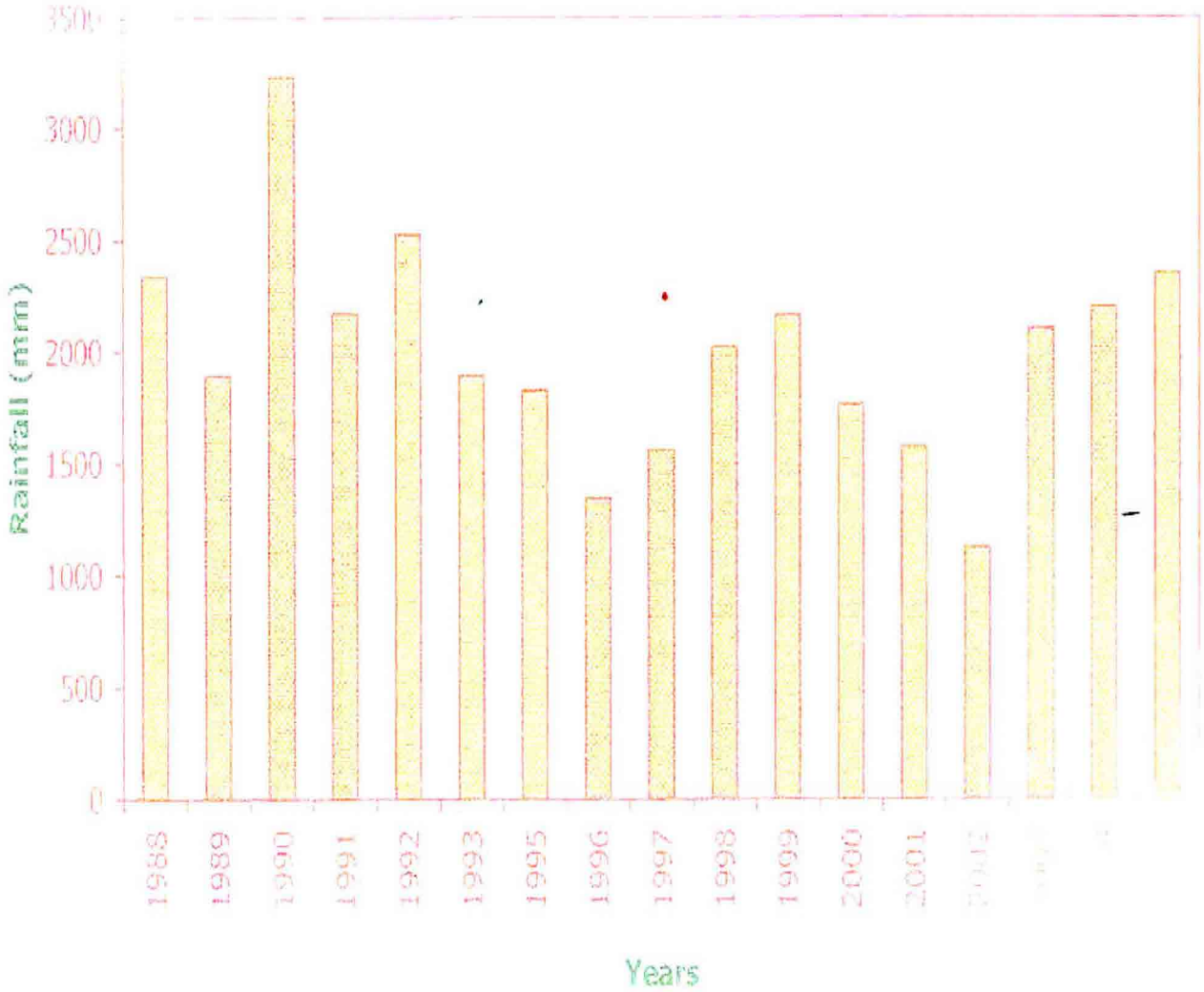


Fig. 3.2 Total yearly rainfall (mm) at Palampur (HP) for the period 1988 to 2005

Table 3.1 Some initial physico-chemical characteristics of the soil before *kharif* 1988

Bulk Density (Mg m^{-3})	1.25
Mechanical separates (%)	
Sand	16.8
Silt	52.7
Clay	30.1
Textural class	Silty clay loam
Soil reaction (1:2.5 soil solution ratio)	Acidic (pH 5.8)
Organic carbon (g kg^{-1})	8.8
Available nutrients (kg ha^{-1})	
N	170
P	8.0
K	76.0
Cation exchange capacity [c mol (p^+) kg^{-1}]	10.0
DTPA extractable micronutrients (mg kg^{-1})	
Fe	10.0
Mn	12.5
Zn	0.62
Cu	1.21
Taxonomic classification	Typic Hapludalfs

3.2 Field Studies

3.2.1 Experimental Details

The long term field experiment was started during *Kharif* 1988 with four levels of lantana incorporation (0, 10, 20 and 30 t ha^{-1} on fresh weight basis) and three tillage practices (compacted, puddled and non-puddled). The residual effect of lantana incorporation and tillage practices were evaluated on subsequent wheat crop every year upto *Rabi* 1992-93. However, from *Kharif* 1993, the experiment was modified and tillage practices were replaced by three levels of

nitrogen viz. 50, 75, 100 percent of the recommended dose of 90 kg ha^{-1} to rice. Nitrogen levels to wheat were reversed to 100, 75 and 50 percent of the recommended 120 kg ha^{-1}. These treatment combinations of four levels of lantana and three levels of nitrogen continued upto *Rabi* 1996-97. However, looking into the build-up of nutrients, the three nitrogen levels were further modified to 33, 66 and 100 percent of the recommended N and K to rice from *Kharif* 1997. The application of phosphorous to rice was totally omitted. The N, P and K application to wheat was also modified to 66 percent of their recommended levels. The recommended dose of K to rice was 33.3 kg ha^{-1}. The recommended dose of N, P_2O_5 and K_2O to wheat were 120, 26 and 25 kg ha^{-1}, respectively. The whole amount of K was applied at transplanting of rice whereas 50 percent of N was applied 10 days after transplanting and remaining 50 percent in two splits at 20 and 40 days after transplanting. Similarly in wheat, whole of P and K and 50 percent N was top dressed in two equal splits at crown root initiation and flowering stages. The sources of fertilizers used were urea, single-super phosphate and muriate of potash for N, P and K, respectively. Lantana was incorporated 10-15 days before puddling/transplanting of rice. Lantana twigs were manually chopped into small pieces (4-5 cm size), spread uniformally over the entire plot and incorporated into the surface soil (0-0.15 m) with the help of spades. The plots were irrigated and left as such for 10-15 days. The rice seedlings were transplanted at a spacing of 20 x 15 cm with 2-3 seedlings per hill. The rice variety used was RP-2421. After the harvest of rice crop, plots were manually prepared for sowing of wheat. The wheat was sown @ 100 kg ha^{-1} in a row to row distance of 22.5 cm. All standard cultural practices

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were followed during the whole period of rice and wheat growth. Experimental plots were kept free of weeds by manual weeding from time to time. The average chemical composition of lantana is presented in Table 3.2

Table 3.2 Average chemical composition of lantana biomass (dry weight basis)

C	N	P	K	Zn	Cu	Fe	Mn	C:N	C:P
← (%) →				← mg kg^{-1} →					
52.50	2.50	0.25	1.40	12.00	10.00	24.20	33.00	21:1	210.1

Details of treatments

A- Lantana levels = 4 (0, 10, 20 and 30 t ha^{-1} on fresh weight basis)

B- Fertilizer levels = 3 (33, 66 and 100 percent of recommended dose)

Details of levels of fertilizers

Crop	N	P	K
	Per cent of recommended dose		
Rice	33	0	33
Rice	66	0	66
Rice	100	0	100
Wheat	66	66	66

Total treatment combinations	:	4 x 3
Number of replications	:	3
Plot size	:	5m x 2m =10 m^2
Total Plots	:	12 x 3 =36
Design	:	Randomized Block Design

3.3 Laboratory Studies

3.3.1 Soil Quality Assessment

Soil samples were collected to a depth of 0-0.15 and 0.15-0.30 m after the harvest of wheat (*Rabi*, 2004-2005) crop. Some quantity of fresh soil samples were stored in polyethylene bags in refrigerator at 4^0C for microbiological studies and the remaining was air-dried, ground to pass through a 2 mm sieve and subjected to physical and chemical characterization.

3.3.1.1 Physical Characterization

Bulk density (BD)

Bulk density was determined in quadruplets with a core sampler having 13.4 cm height and 10.4 cm diameter following the procedure of Singh (1980). The soil was sampled from 0 - 0.15 and 0.15 - 0.30 m soil depths. The bulk density was expressed on dry weight basis.

Saturated hydraulic conductivity

Undisturbed soil cores having soil column of 13.4 cm height and 10.4 cm diameter were collected from 0 - 0.15 and 0.15 - 0.30 m depths in quadruplets. Saturated hydraulic conductivity (Ks) was determined by constant head method and calculated by following Darcy's equation (Richard, 1954) as:

$$Ks = (Q/AT) / (L/ L+H)$$

Where:

Ks = Saturated hydraulic conductivity

Q = Steady state volume of outflow from entire soil samples (cm^3)

A = Cross sectional area of permeameter (cm^2)

T = Time (min.)

L = Length of the soil column (cm)

H = Depth of water above the soil (cm)

3.3.1.2 Chemical Characterization

Processed soil samples were analyzed for chemical characteristics by using standard procedures as outlined in Table 3.3.

Table 3.3 Analytical techniques followed for chemical characterization of soils

Parameter	Method	Reference
pH (1:2.5::soil:water)	Glass electrode pH meter	Jackson (1973)
Organic carbon	Rapid titration	Walkley and Black (1934)
Available nitrogen	Alkaline permanganate	Subbiah and Asija (1956)
Available phosphorus	Olsen's method	Olsen *et al.* (1954)
Available potassium	Neutral normal ammonium acetate	Hanway and Heidal (1952)
Available sulphur	Turbidimetric method	Chesnin and Yien (1950)
Fe, Mn, Zn, Cu	Atomic absorption Spectrophotometer (AAS)	Lindsay and Norvel (1978)

3.3.1.3 Biological Characterization

The biological characterization of soils was carried out in respect of microbial biomass carbon, nitrogen, phosphorus and sulphur and microbial count by the procedures outlined below:

Microbial biomass carbon

Soil microbial biomass carbon (SMB-C) was determined by Fumigation-extraction method as per the procedure given by Vance *et al.* (1987). Twenty g soil (air dried) was fumigated with 50 ml of ethanol free chloroform in a desiccator. Ethanol free chloroform was prepared by passing 100 ml chloroform through a glass column containing 75 g basic aluminium oxide (Vogel, 1978). After 24 hours fumigation at 25°C, chloroform was removed by repeated evacuations. The fumigated soil samples were extracted with 80 ml of 0.5 M K_2SO_4 for 30 minutes on a rotary shaker at 160 rpm and filtered. 8ml of filtrate was refluxed with 2ml of $K_2Cr_2O_7$ and 15 ml of diacid mixture (H_2SO_4: H_3PO_4 : : 2:1) for half hour on hot plate at 150°C with three drops of phenanthroline indicator solution. After cooling, the mixture was titrated with Ferrous Ammonium Solution. Similar procedure was followed for non-fumigated soil samples except that these samples were not fumigated.

Soil microbial biomass C was calculated as under:

SMB-C (mg kg^{-1}) = 2.64 (Extractable C in fumigated soil- Extractable C in non-fumigated soil)

Where:

2.64 = K_c Factor (Vance *et al.*, 1987)

Microbial biomass nitrogen

To 20 ml of K_2SO_4 extract prepared as for microbial biomass C estimation, 10 ml of digestion mixture and 300 mg of Zn powder was added and allowed to stand for 24 hours. Thereafter, 0.6 ml of 0.19M $CuSO_4$ and 5ml of conc. H_2SO_4 was added and digested on Kjeldatherm digester for 2 hours. The digested mixture was then analysed for non-fumigated samples (Brookes *et al.*, 1985).

Soil microbial biomass N was calculated as under:

SMB-N (mg kg^{-1}) = 2.22 (Extractable N in fumigated soil- Extractable N in non-fumigated soil)

Where:

2.22 = K_n factor

Microbial biomass phosphorus

For the determination of soil microbial biomass phosphorus (SMB-P), ten g soil sample (oven dry basis) was shaken with 200 ml 0.5 M $NaHCO_3$ (1:20:: soil:0.5 M $NaHCO_3$) in 250 ml conical flasks for 30 minutes at 25^0C and 150 rpm in an orbital shaker (Brookes *et al.*, 1982). SMB-P was determined in both fumigated and non-fumigated soil samples under similar set of conditions and values were measured at 660 nm wavelength using ascorbic acid method (Olsen *et al.*, 1954).

Microbial biomass sulphur

Soil microbial biomass sulphur (SMB-S) determination was made in fumigated and non-fumigated soil samples. Twenty g soil was shaken for 30 minutes with 20 ml of 10 mM $CaCl_2$ solution (Wu *et al.*, 1994). The turbidity was measured at 420 nm wavelength.

3.3.1.4 Microbial count

Microbiological studies in respect of bacterial, fungal and actinomycetes count were carried out using standard plate count technique (Wollum, 1982)

Preparation of dilution series: One gram of each of the moist soil sample was transferred to 99 ml sterilized distilled water blank under aseptic conditions resulting in 10^{-2} dilution. From this dilution blank, 1 ml was taken and added to 9 ml of dilution blank to make further serial dilutions up to 10^{-6}.

Spread plate: Different media were employed for different types of soil microorganisms. Nutrient Agar, Rose Bengal Agar (RBA) and Ken Knight and Muncie Agar were used for bacteria, fungi and actinomycetes, respectively. Streptomycin (30 µg/ml) was added to RBA medium just before its pouring into petri plates to inhibit bacterial growth. About 0.1 ml of the suspension from respective blanks was taken and spread over the solid media in the sterilized petri plate with the help of glass spreader under aseptic conditions. After spreading, the plates were incubated at different temperatures for different time periods depending on the growth of microorganism as shown in Table 3.4. Colonies on each plate were then counted after incubation period and the plates showing colonies in the range of 30-300 were selected for determination of microbial counts.

Table 3.4 Temperature and time of incubation for different nutrient media

S. No.	Media	Temperature range (^{0}C)	Incubation period (Days)
1.	Nutrients Agar	30-32	4-6
2.	Rose Bengal Agar	28	2
3.	Ken Knight and Muncie Agar	28	7-10

Calculation of microbial count: Average number of colonies per plate for a given dilution was multiplied by dilution factor to obtain the viable count per gram soil.

3.3.2 Soil Organic Matter (SOM) Pools

3.3.2.1 Active Pools of Soil Organic Matter

Water-soluble organic carbon (WS-OC)

Water soluble organic carbon in soil was determined as per the procedure outlined by McGill *et al.* (1986). Five gram freshly drawn field-moist soil sample (within 24 hours of sampling) was shaken with 10 ml (1:2 :: soil : water) distilled water for 60 minutes followed by 30 minutes centrifugation at 10,000 rpm. The supernatant was then filtered and 5 ml aliquot was taken in conical flask and treated with 5 ml 0.07 N $K_2Cr_2O_7$, 10 ml concentrated H_2SO_4 and 5 ml ortho-phosphoric acid. The sample was mixed carefully and digested at 150^0C for 30 minutes using digestion block and cooled to room temperature. Thereafter, 1ml of diphenylamine indicator was added and titrated against 0.035 N ferrous ammonium sulphate prepared in 0.4 M H_2SO_4 till the appearance of dark green colour as end point. Simultaneously a blank was also run. WS-OC was calculated as follows:

$$\text{WS-OC (\%)} = \frac{(B-S) \times 0.035 \times 0.003 \times 100}{\text{Weight of soil}}$$

Where:

0.035 = Normality of ferrous ammonium sulphate

B = Quantity of ferrous ammonium sulphate consumed in blank titration

S = Quantity of ferrous ammonium sulphate consumed in sample titration

Water soluble carbohydrates (WS-CHO)

Five gram air dried soil sample passed through 1 mm sieve was hydrolysed for 24 hours on a steam bath with 10 ml of 3 N H_2SO_4 per g of soil (1:10:: Soil:H_2SO_4). The material was placed in 125 ml Erlenmeyer flasks, with the mouths covered by funnel to minimize evaporation, the contents were maintained at about 85^{0}C throughout the hydrolysis.

Aliquots of soil hydrolyzates were neutralized by adding excess of 5 ml of 6 N NaOH for neutralization. The hydrolyzates, while still hot, were passed through silica buchner funnel and the residues were washed with 10 ml hot water per gram soil. The filtrates were cooled to room temperature and made to 100 ml for determination of water-soluble carbohydrates. Five ml of aliquot was then taken in a test tube and 10 ml of 0.2 per cent anthrone reagent was added to it and shaken well. The concentration of water-soluble carbohydrates was measured at 625 nm by using spectronic 20-D (Brink *et al.*, 1960).

3.3.2.2 Slow Pool of Soil Organic Matter

Laboratory studies were carried out to determine the content of slow pool of soil organic matter in macro- and micro-aggregates of soils. The whole soil sample (>2000 µm) was used for aggregation by wet sieving method (Cambardella and Elliot, 1992). Four sub-samples each weighing 20 g were sieved by Yoder's apparatus through a series of sieves to obtain different size fractions viz; >2000 µm, 2000-1000 µm, 1000-500 µm, 500-250 µm, 250-125 µm, 125-53 µm and <53 µm. The represented soil samples were suspended in water on the largest sieve for 5 minutes through Yoder's apparatus before commencement of sieving. Aggregate disruption was accomplished by moving the sieve inside the water 3 cm vertically 50 times for a period of 2 minutes.

The soil passing through a particular sieve was then transferred to the next finer size sieve and the process was repeated four times. Aggregate/material remaining on the sieves was backwashed into round aluminum pans and dried for overnight at 50^0C in a forced air oven. The dried aggregate size fractions were weighed and stored at room temperature. Soil samples for each aggregate size except those for finer class were ground to pass through 2000 µm size to determine total organic carbon by wet oxidation method (Walkley and Black, 1934).

$$\text{Organic C (\%) in each aggregate size fraction} = \frac{(B-S) \times 0.5 \times 0.003}{\text{Weight of soil}} \times 100$$

Where:

0.5 = Normality of ferrous ammonium sulphate

B = Quantity of ferrous ammonium sulphate consumed in blank titration

S = Quantity of ferrous ammonium sulphate consumed in sample titration

3.3.2.3 Passive Pools of Soil Organic Matter

Humic acids (HA) and fulvic acids (FA) forms an important fraction of passive pools of soil organic matter. These acids were estimated by separation method after extracting the soil with freshly prepared 0.5 N NaOH at pH 13.0 and washed with 0.1 N HCl as per extraction procedure given by Stevenson (1994).

Humic acid (HA)

Forty gram soil sample was taken in a poly-ethylene centrifuge tube and treated with 200 ml 0.5 N NaOH solution. The mixture was shaken for 12 hours on a mechanical shaker and centrifuged at 3000 rpm for 10 minutes. Dark

coloured supernatant liquid was filtered and the pH of filtrate was adjusted to 1.0 with concentrated HCl. The residual soil was treated with additional 200 ml 0.5 N NaOH, shaken for 12 hours, centrifuged at 3000 rpm for 10 minutes and filtered. Later, 200 ml distilled water was added to the soil residue of principal extraction followed by shaking for 30 minutes, centrifugation at 3000 rpm for 30 minutes and filtration. The supernatant obtained was added to the previous extracts and pH was adjusted to 1.0 with concentrated HCl. The extract was then allowed to stand overnight to get HA fraction. The supernatant liquid was siphoned off as FA and the suspension was centrifuged off at 3000 rpm for 10 minutes for the collection of humic acid precipitates.

The dissolution and precipitation process was repeated until the acid supernatant became almost colourless. Humic acid was washed with distilled water until free of chlorides, dried in rotary evaporator, ground to a fine powder, weighed and reported as percentage of HA in soil as:.

$$\text{HA (\%)} = \frac{A}{W} \times 100$$

Where:

A = Weight of humic acid in mg

W = Weight of soil in mg

In order to express the HA content as per cent of organic matter; the organic carbon content in a particular soil sample was multiplied with 1.724. The content of HA as per cent of organic matter was then worked out as under:

$$\text{Humic acid (\% of organic matter)} = \frac{\text{Humic acid (\%)}}{\text{Organic matter (\%)}} \times 100$$

Fulvic acid (FA)

The acid extract collected in HA preparation was FA. A known aliquot was taken, evaporated and dried. The dried residue was weighed and reported as percentage of FA in soil on moisture and ash free basis as under:

$$FA\ (\%) = \frac{B}{W} \times 100$$

Where:

B = Weight of fulvic acid in mg

W = Weight of soil in mg

To express the FA content as per cent of organic matter; the organic carbon content in a particular soil sample was multiplied with 1.724. The content of FA as per cent of organic matter was then worked out as under:

$$\text{Fulvic acid (\% of organic matter)} = \frac{\text{Fulvic acid (\%)}}{\text{Organic matter (\%)}} \times 100$$

3.3.2.4 Active Pools of Nutrients

The active pools of nutrients were determined by the methods as outlined in Table 3.5.

Table 3.5 Analytical methods used for the determination of active pools of nutrients

Parameter	Method
Water soluble N	Bremmer and Keeney (1965)
Water soluble P	Murphy and Riley (1962)
Water soluble S	Johnson and Nishita (1952)

3.3.2.5 Passive Pool of Nutrients

The passive pool of nutrients viz; humic acid – N, S and fulvic acid- N and S were determined by automated CHNS analyzer.

3.4 Validation of Carbon Models

3.4.1 Roth-C Model

The Roth–C model developed by Coleman and Jenkinson (1996) was used to simulate the turnover of organic carbon in Typic Hapludalf of western Himalayas. The model was tested in the present study against SOC stocks from 1988 to 2004 as influenced by different nutrient management treatments in long-term fertilizer experiment established at Palampur (HP) in 1988. For the validation of Roth-C model under the present nutrient management practices and climatic situations, it was necessary to have initial SOC stock of the year 1988 which was 16.5 t ha^{-1} and assumed to be in steady state. Since the initial plant residues or root biomass was not known, Roth-C was to run equilibrium in reverse mode by fitting the initial SOC stock of 16.5 t ha^{-1}. This stock was distributed uniformily in twelve months at the rate of 1.38 t C ha^{-1} to calculate the initial plant inputs by way of plant residues and root biomass. A soil cover factor of one was used in all the months assuming that there was no fallow period before the start of experiment. Similarly, as suggested by Jenkinson *et al.* (1992) for agricultural crop lands a ratio of 1.44 between DPM (Decomposable plant material)/RPM (Resistant plant material) was also used. The silty clay loam soil with 30.1 per cent clay and 8.8 g kg^{-1} initial SOC stock was ploughed to a depth of 0.15 m. The rice-wheat cropping sequence was followed over the years. Since the radiocarbon age of soil was unknown, inert organic matter (IOM) was calculated from the initial SOC stock using the equation proposed by Falloon *et al.* (1998) as under:

$$IOM = 0.049 \times SOC^{1.139}$$

The estimated value of IOM was 1.194 t C ha^{-1} $year^{-1}$ for soil organic carbon stock of 16.5 t ha^{-1}. The data on monthly weather parameters viz; total rainfall, mean air maximum temperature and evaporation were collected from the meteorological observatory of Himachal Pradesh Krishi Vishvavidyalaya, Palampur, HP since 1988. The actual weather file was used to set the initial SOC stock of the site under investigation. Once the initial C stock was maintained, individual land management files for each of the nine treatments were created for every year.

The individual scenario files were then created for each treatment for 17 years and model was run to compare the measured C values with the values predicted by the Roth-C for each treatment. The performance of the model was evaluated on the basis of root mean square (RMSE) as given by Smith *et al.* (1997).

3.4.2 Carbon and Nitrogen Dynamics (CANDY) Model

The carbon and nitrogen dynamics (CANDY) system is an integration of different simulation modules and a database system for model parameters like soil and weather management data (Franko *et al.*, 1995). The CANDY model has been created to simulate processes in agro-ecosystems, which are described by the following modules: climate, soil, crop and management (Franko and Mirschael, 2001).

The inputs required to generate climate module are daily values for precipitation, air temperature and sun shine duration. The soil module required data on soil physical properties like bulk density, texture and field capacity.

The organic matter turnover module and N dynamics is the main component of CANDY model. The model is based on the assumption that input of plant residues (t ha^{-1}) occurred only after the harvest of crop.

In the absence of many of the required parameters, the CANDY model could not be used in the present study.

3.4.3 Nutrients' Uptake Studies

The grain and straw yields of rice and wheat were recorded from *kharif* 2004 to *Rabi* 2005-06. The grain and straw yield samples for two rice and two wheat seasons were also taken for their chemical analysis.

Collection, processing and analysis of plant samples for nutrient uptake studies

The samples were oven dried at 60^0C. The dried samples were then ground in a wiley mill fitted with stainless steel parts to pass through 1 mm sieve and kept in paper bags for subsequent analysis. The analytical procedures followed for the determination of N, P and S in plant samples are outlined in Table 3.6.

Table 3.6 The analytical methods employed for plant analysis

S. No.	Parameter	Method employed	Reference
1.	Nitrogen	Micro-kjeldahl method	Jackson (1973)
2.	Phosphorus	Vanado-molybdo-phosphoric acid yellow colour method	Jackson (1973)
3.	Sulphur	Turbidimetric method	Chesnin and Yien (1950)

The nutrients' uptake was calculated by multiplying per cent concentration of a particular nutrient with grain and straw yields. The uptake of the nutrient obtained in respect of grain and straw were summed up in order to compute the amount of total nutrient removal by the crop.

3.5 Statistical Analysis

The data so generated from field and laboratory studies were statistically analysed by the methods elucidated in the book "Statistical Procedures for Agricultural Research" by Gomez and Gomez, (1984) through the requisite statistical computation so as to predict the effect of treatments on various parameters. Attempt has also been made to work out the relationship between SOM pools, nutrient's supply and crop productivity.

Results

Chapter IV

RESULTS

The results emanating from the present investigation entitled, "Carbon sequestration and nutrient dynamics of a long-term lantana amended soil under rice-wheat system" have been presented in this chapter under the following main heads:

4.1 Physical Properties

4.2 Biological Properties

4.3 Chemical Properties

4.4 Carbon Sequestration and SOM Dynamics

4.5 Yield and Nutrient Uptake

4.6 Relationship between SOM Pools, Nutrient's Supply and Crop Productivity

4.7 Interrelationship among different SOM Pools

4.8 Validation of Carbon Models

4.1 Physical Properties

The soil samples collected after the harvest of *Rabi* (2004-05) crop were analyzed for bulk density and hydraulic conductivity.

Bulk density (BD)

The data pertaining to the effect of lantana addition and fertilizer application on soil BD are presented in Table 4.1. In general, soil BD under different treatments varied from a maximum value of 1.21 Mgm^{-3} to a minimum

value of 1.10 Mgm^{-3} in 0-0.15 m. The interaction between lantana and fertilizer levels on BD was not significant at any soil depths, hence only the main effects of these two factors are given in Table 4.1. The values of BD were generally higher in lower depth (1.12 to 1.30 Mgm^{-3}) than in surface soils (1.10 to 1.21 Mgm^{-3}). The effect of fertilizer application was not found significant on BD in any of the soil depths, however, the addition of lantana from 10 to 30 t ha^{-1} decreased BD significantly and consistently in both the soil depths. The BD in 0-0.15 m soil depth was 1.21 Mgm^{-3} under no lantana addition which was reduced to 1.10 Mgm^{-3} under 30 t ha^{-1} lantana addition. Similarly, the BD values were reduced from 1.30 Mgm^{-3} under no lantana application to 1.12 Mgm^{-3} under 30 t ha^{-1} lantana application in 0.15-0.30 m soil depth. The BD values were, in general, higher at 0.15-0.30 m soil depth with all levels of fertilizer application than its respective values in the surface layer.

Table 4.1 Long-term effect of lantana addition and fertilizer application on soil bulk density (Mgm^{-3})

Lantana addition (t ha^{-1})	0–0.15 m	0.15–0.30 m
0	1.21	1.30
10	1.16	1.24
20	1.10	1.18
30	1.10	1.12
LSD = (0.05)	0.04	0.05
Fertilizer levels (% of the recommended dose)		
33	1.12	1.21
66	1.12	1.20
100	1.11	1.20
LSD = (0.05)	NS	NS

Saturated hydraulic conductivity (SHC)

Similar to soil bulk density, the interaction effect of lantana addition and fertilizer application was not found significant on SHC. Therefore, only the main effect of lantana addition and fertilizer on SHC has been given in Table 4.2. Like BD, the effect of fertilizer levels was not significant on SHC of the soils. However, the addition of lantana had significant effect on this soil property. The continuous 17th addition of lantana to increased SHC significantly and consistently in both the soil depths. The increase due to lantana addition in surface soil depth was from 0.0143 cm/min in control to 0.0242 cm/min under 30 t ha^{-1} lantana. Likewise, the increase in SHC was from 0.00080 cm/min under no lantana application to 0.00463 cm/min. under 30 t ha^{-1} lantana application in sub surface soil depth. In general, the values of SHC were quite low in lower soil depths in comparison to surface depth.

Table 4.2 Long-term effect of lantana addition and fertilizer application on saturated hydraulic conductivity (Ks) (cm/min)

Lantana addition (t ha^{-1})	0–0.15m	0.15–0.30 m
0	0.0143	0.0008
10	0.0152	0.0012
20	0.0185	0.0035
30	0.0242	0.0046
LSD = (0.05)	0.0002	0.00005
Fertilizer levels (% of the recommended dose)		
33	0.0182	0.0025
66	0.0179	0.0025
100	0.0179	0.0025
LSD = (0.05)	NS	NS

4.2 Biological Properties

The soil samples collected from surface and sub-surface soil depths after the harvest of *Rabi* (2004-05) wheat were analyzed for different biological properties. The results pertaining to biological properties are given in this section under following sub-heads:

4.2.1 Carbon Pools

4.2.1.1 Soil Organic Carbon (SOC)

4.2.1.2 Active Pools

4.2.1.3 Slow Pools

4.2.1.4 Passive Pools

4.2.2 Soil nitrogen, Phosphorus and Sulphur Pools

4.2.2.1 Active Pools

4.2.2.2 Passive Pools

4.2.3 Microbial Count

4.2.1 Carbon Pools

4.2.1.1 Soil Organic Carbon (SOC)

A perusal of data in Table 4.3 reveals that irrespective of lantana addition and fertilizer application, average organic carbon was 12.3 g kg^{-1} in surface layer and 8.6 g kg^{-1} in the sub-surface layer, indicating a decrease of about 30 per cent in the sub-surface layer in comparison to the surface layer. The SOC content was not influenced significantly with the application of fertilizers in both the soils depths. In contrast, the addition of lantana resulted in significant and consistent improvement in SOC content when compared with control.

Table 4.3 Long-term effect of lantana addition and fertilizer application on soil organic-C (g kg^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	9.2	9.5	9.6	9.4
10	11.8	12.3	12.6	12.2
20	12.9	13.5	13.7	13.4
30	13.9	14.0	14.2	14.0
Mean	11.9	12.3	12.5	
LSD = (0.05)	F=NS	L=0.4	FxL=NS	
		(0.15 – 0.30 m)		
0	6.9	7.6	7.9	7.5
10	8.0	8.4	8.8	8.4
20	8.6	8.9	9.2	8.9
30	9.4	9.6	9.8	9.6
Mean	8.2	8.6	9.0	
LSD = (0.05)	F=NS	L=0.4	FxL=NS	

Irrespective of fertilizer application, the average increase in SOC with 10, 20 and 30 t ha^{-1} lantana addition over the control was about 30, 43 and 49 per cent in surface layer and 12, 19 and 28 per cent in sub-surface layer, respectively. The interaction between lantana addition and fertilizer application was not found significant on SOC content in any of the soil depth.

4.2.1.2 Active Pools

Water soluble organic carbon (WS-OC)

In general, WS-OC ranged from a minimum value of 40 to a maximum value of 168 mg kg^{-1} in surface layer and from 28 to 117 mg kg^{-1} in sub-surface soil (Table 4.4). The average WS-OC in surface layer was found to the tune of 101 mg kg^{-1} whereas it was 70 mg kg^{-1} in sub-surface layer indicating thereby that in sub-surface layer the WS-OC was about 31 per cent lower than in surface layer. It is interesting to note, that though WS-OC was quite less in sub-surface layer but its percentage of soil OC was almost the same in both the soil layers (0.83 per cent).

In general, irrespective of fertilizer application, increasing levels of lantana addition from 10 to 30 t ha^{-1} increased WS-OC significantly and consistently over the control in both the soil depths, the per cent increase being 67, 127 and 196 per cent in surface layer and 70, 141 and 206 per cent in sub-surface layer. Similarly, fertilizer application from 33 to 100 per cent of the recommended dose (RD) also increased WS-OC significantly and consistently in both the soil depths. The interaction between lantana addition and fertilizer application on WS-OC was found significant only in surface depth of the soil.

Table 4.4 Long-term effect of lantana addition and fertilizer application on WS-OC (mg kg^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	40	51	62	51
10	70	86	99	85
20	100	118	130	116
30	133	154	168	151
Mean	86	102	115	
LSD = (0.05)	F=5	L=8	LxF=12	
		(0.15 – 0.30 m)		
0	28	35	39	34
10	48	58	68	58
20	70	81	95	82
30	92	103	117	104
Mean	60	69	80	
LSD = (0.05)	F=4	L=7	FxL=NS	

The application of fertilizer did not influence the build up of WS-OC when it was applied in the absence of lantana addition. However, when fertilizer application was made from 33 to 100 per cent of RD in the presence of lantana addition (10 to 30 t ha^{-1}), it increased WS-OC significantly and consistently. In contrast, the addition of lantana from 10 to 30 t ha^{-1} increased WS-OC under all the levels of fertilizer application. It is worthwhile to mention that the content of WS-OC with the addition of 10 t ha^{-1} lantana under 33 per cent of RD was same as was observed in 100 per cent RD without lantana addition in surface depth. The contents of WS-OC was observed to be much higher under 20 to 30 t ha^{-1} lantana addition with 33 per cent of RD in comparison to 100 per cent RD.

Water soluble carbohydrates (WS-CHO)

Irrespective of lantana addition and fertilizer application, the average WS-CHO was 640 mg kg^{-1} in surface layer and 525 mg kg^{-1} in sub-surface layer. This clearly indicates about 18 per cent reduction in WS-CHO in sub-surface depth as compared to surface depth (Table 4.5). It is interesting to note that inspite of large variation in WS-CHO in surface and sub-surface soil depths, the proportions of WS-CHO as fraction of SOC was the same in both soil depths (about 5.5 per cent). The lantana addition as well as fertilizer application increased WS-CHO significantly and consistently in both the soil depths. The increase in WS-CHO with addition of 10, 20 and 30 t ha^{-1} lantana over its control was 9, 27 and 36 per cent in surface layer and 16, 25 and 37 per cent in sub-surface depth. Similarly, the increase in WS-CHO with 66 and 100 per cent of RD over its 33 per cent dose was observed to be 7 and 19 per cent in surface layer and 10 and 16 per cent in sub-surface layer, respectively. The interaction between lantana addition and fertilizer application was not found significant in any of the soil depths on WS-CHO.

Table 4.5 Long-term effect of lantana addition and fertilizer application on WS-CHO (mg kg^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	495	542	591	543
10	549	572	650	590
20	648	682	739	689
30	668	728	816	737
Mean	590	631	699	
LSD = (0.05)	F=14.7	L=17.0	FxL=NS	
		(0.15 – 0.30 m)		
0	394	453	473	440
10	462	524	545	510
20	514	560	581	548
30	561	605	641	603
Mean	483	536	557	
LSD = (0.05)	F=18.2	L=21.0	FxL=NS	

Soil microbial biomass – Carbon (SMB-C)

Irrespective of lantana addition and fertilizer application, the average SMB-C was 389.5 mg kg^{-1} in surface layer and 262.5 mg kg^{-1} in sub-surface depth, respectively (Table 4.6). The reduction in SMB-C in sub-surface layer was almost the same (33 per cent) as was in case of WS-OC but quite higher in comparison to WS-CHO which was only 18 per cent. Like WS-CHO, the proportion of SMB-C towards soil SOC was almost the same in both the soil depths (3.2 per cent) inspite of large variations in its content in surface and sub-surface soil depths. Like WS-CHO, the contents of SMB-C were significantly affected both by the addition of lantana and fertilizer application in both the soil depths. The four levels of lantana and three levels of fertilizer application increase SMB-C significantly and consistently in both the soil depths, the per cent increase over the control being 14, 31 and 57 in surface layer and 20, 37 and 56 in sub-surface layer under 10, 20 and 30 t ha^{-1} lantana addition. Similarly, the increase under 66 and 100 per cent of RD over the control was 5 and 10 per cent in surface layer and 6 and 13 per cent in sub-surface layer.

The interaction between lantana addition and fertilizer application was found to be significant on SMB-C in both the soil depths. The lantana addition under all the levels of fertilizer application as well as fertilizer application under all the levels of lantana addition increased SMB-C significantly.

Table 4.6 Long-term effect of lantana addition and fertilizer application on SMB-C (mg kg^{-1})

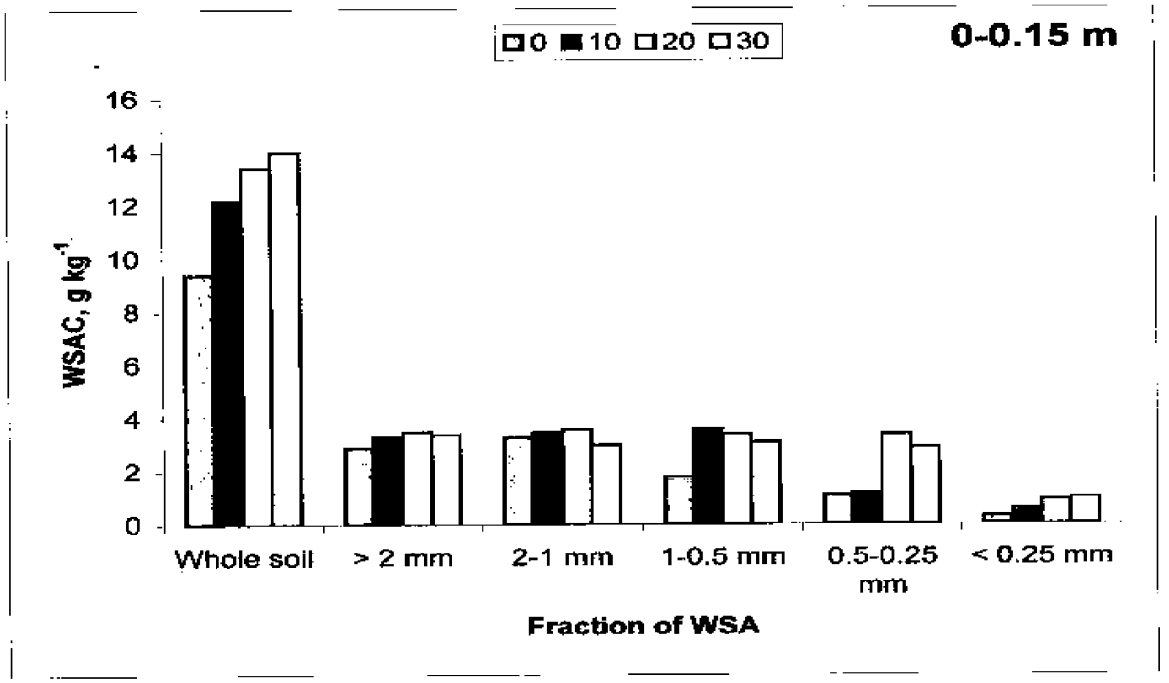
Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
	(0 – 0.15 m)			
0	290	315	325	310
10	340	355	370	355
20	395	403	417	405
30	460	484	520	488
Mean	371	389	408	
LSD = (0.05)	F=3.48	L=4.08	LxF=7.08	
	(0.15 – 0.30 m)			
0	190	205	220	205
10	230	242	263	245
20	268	278	294	280
30	300	320	340	320
Mean	247	261	279	
LSD = (0.05)	F=3.36	L=3.88	LxF=6.72	

4.2.1.3 Slow Pools

Water stable aggregate carbon (WSAC)

The carbon content bound to different size fractions of soils viz., >2, 2-1, 1-0.5, 0.5-0.25 and <0.25 mm is represented as slow pool of organic matter and designated as water stable aggregate carbon (WSAC). The effect of fertilizer as well as the interaction between lantana and fertilizer application on WSAC was not found significant in any of the soil size fractions in either of the soil depths, hence only the main effect of lantana addition was given in Table 4.7 and Figure 4.1. Among different size fractions, the WSAC, in general, was highest in 2-1 mm size followed by >2mm and 1-0.5 mm size in both the soil depths. Like total SOC in the soil, the WSAC was also high in all the soil size fractions in surface layer as compared to sub-surface soil depth. The different soil size fractions with respect to WSAC was found in the order of 2-1mm > 2mm > 1.0-0.5 mm > 0.5-0.25 mm < 0.25 mm in both soil depths.

In general, the WSAC content increased in all the soil size fractions with increase in lantana addition from 10 to 30 t ha^{-1} in both the soil depths. The range of WSAC found in per cent of total SOC ranged from 24 to 31, 21 to 35, 19 to 30, 10 to 25 and 3 to 7 in surface layer and 26 to31, 29 to 37, 17 to 25, 11 to 22 and 4 to 8 in sub-surface soil depth in >2, 2-1, 1-0.5, 0.5-0.25 and <0.25 mm, respectively. In general, if WSAC in two soil size fraction viz., 1-0.5 mm and 0.5-0.25 mm was grouped together, it was found that more than 50 per cent of total SOC is retained in these two soil size fractions in both the soil depths. The per cent retention of WSAC as per cent of total SOC which was retained in soil size



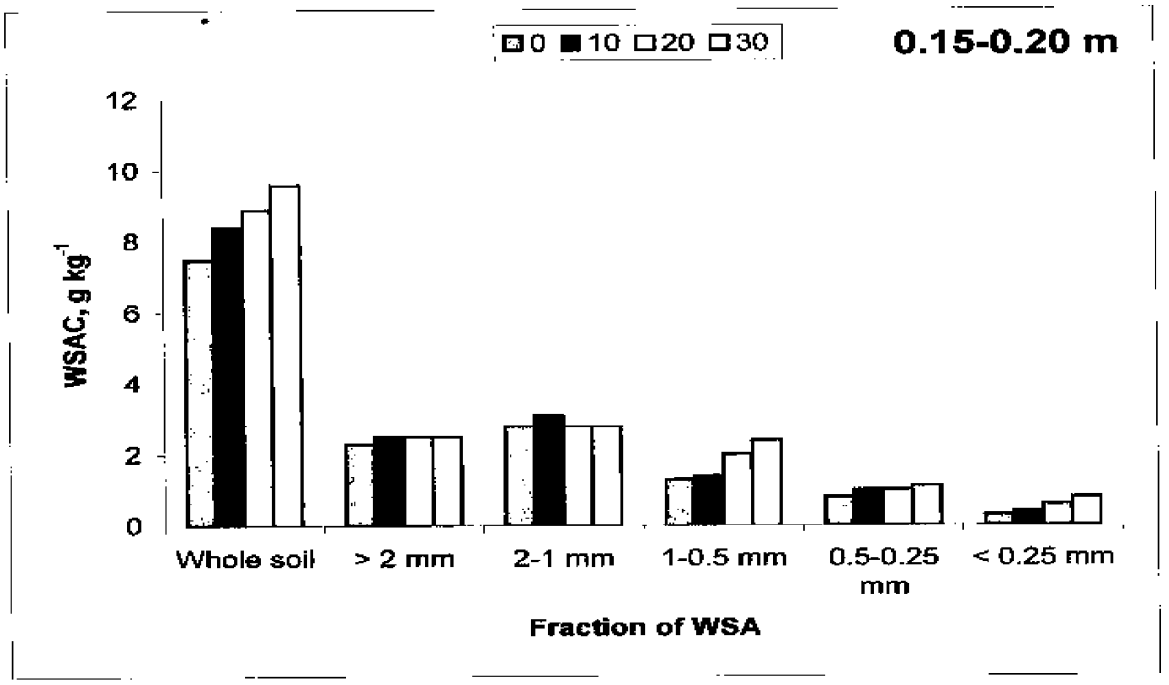


Fig. 4.1 Long-term effect of lantana addition and fertilizer application on water stable aggregate carbon (WSAC), g kg^{-1}

fraction of < 0.5 mm was found in the range of 15 to 32 in surface depth and 15 to 19 in sub-surface soil depth. It is interesting to note that in finer soil size fractions, the per cent retention of WSAC was increased with increase in lantana addition.

Table 4.7 Long-term effect of lantana addition and fertilizer application on water stable aggregate carbon (WSAC), g kg^{-1}

Lantana addition (t ha^{-1})	Fraction of WSA					
	Whole soil	> 2 mm	2-1 mm	1-0.5 mm	0.5-0.25 mm	< 0.25 mm
			(0 – 0.15 m)			
0	9.4	2.9	3.3	1.8	1.1	0.3
10	12.2	3.3	3.5	3.6	1.2	0.6
20	13.4	3.5	3.6	3.4	3.4	0.9
30	14.0	3.4	3.0	3.1	2.9	1.0
LSD= (0.05)	0.40	0.10	0.10	0.13	0.11	0.09
			(0.15 – 0.30 m)			
0	7.5	2.3	2.8	1.3	0.8	0.3
10	8.4	2.5	3.1	1.4	1.0	0.4
20	8.9	2.5	2.8	2.0	1.0	0.6
30	9.6	2.5	2.8	2.4	1.1	0.8
LSD = (0.05)	0.40	0.09	0.10	0.08	0.08	0.08

4.2.1.4 Passive Pools

Humic acid – Carbon (HA-C)

The HA-C content ranged from a minimum value of 0.13 to a maximum value of 0.44 g/100g of soil in surface soil depth and from 0.10 to 0.28 g/100g of soil in sub-surface soil depth with average values of 0.28 and 0.19 g/100g of soil in surface and sub-surface soil depths, respectively (Table 4.8). The average decrease in HA-C was about 32 per cent in sub-surface soil depth when compared with surface soil depth. Irrespective of lantana and fertilizer levels, the average contribution of HA-C towards SOM and SOC was 13 and 16 per cent in surface depth and 18 and 21 per cent in sub-surface soil depth, respectively. The increasing levels of lantana addition increased significantly and consistently the HA-C content in both the soil depths. The per cent increase under 10, 20 and 30 t ha^{-1} lantana addition over the control was 45, 55 and 65 per cent in surface layer and 27, 33 and 47 per cent in sub-surface layer, respectively. Similarly, fertilizer application at the rate of 66 and 100 per cent also increased HA-C significantly and consistently over 33 per cent, the increase being 56 and 12 per cent in surface depth and 46 and 92 per cent in sub-surface depth, respectively.

It is noteworthy to indicate that the contribution of HA-C towards SOM and SOC increased with increase in lantana levels as well as fertilizer application in both soil depths. The per cent contribution towards SOM in surface layer under 10 to 30 t ha^{-1} lantana addition varied from 14 to 13 per cent whereas the contribution of HA-C towards SOC was about 23 per cent. Almost similar contribution of HA-C towards SOM and SOC were observed in sub-surface soil

Table 4.8 Long-term effect of lantana addition and fertilizer application on humic acid-Carbon (g/100g of soil)

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
	(0 – 0.15 m)			
0	0.13	0.20	0.27	0.20
10	0.19	0.29	0.39	0.29
20	0.20	0.31	0.42	0.31
30	0.21	0.33	0.44	0.33
Mean	0.18	0.28	0.38	
LSD = (0.05)	F=0.006	L=0.008	LxF=NS	
	(0.15 – 0.30 m)			
0	0.10	0.15	0.20	0.15
10	0.13	0.19	0.25	0.19
20	0.14	0.20	0.27	0.20
30	0.16	0.22	0.28	0.22
Mean	0.13	0.19	0.25	
LSD = (0.05)	F=0.004	L=0.007	LxF=NS	

depths also. As far as average contribution of HA-C towards total SOM and SOC was concerned, it was interesting to mention that there was not much difference between two depths of the soils. The interaction between lantana addition and fertilizer application on HA-C was not found significant on any of the soil depth.

Fulvic acid - Carbon (FA-C)

The data with respect to FA-C have been given in Table 4.9. A perusal of this table indicates that FA-C content in general ranged from 0.14 to 0.44 g/100g of soil in surface depth and from 0.11 to 0.29 g/100g of soil in sub-surface depth. The minimum FA-C was found under no lantana application alongwith 33 per cent of fertilizer application and maximum under 30 t ha^{-1} lantana addition along with 100 per cent of fertilizer dose in both the soil depths. In general, the content of FA-C was about 5 per cent higher in comparison to HA-C in both the soil depths. Irrespective of lantana and fertilizer application, the average FA-C was 0.29 per cent in surface layer and 0.20 per cent in sub-surface layer, indicating a decrease of about 31 per cent which was almost equal as was observed in case of HA-C. The average contribution of FA-C towards SOM was 13.7 per cent in surface depth and 13.5 per cent in sub-surface depth. The corresponding values towards its contribution to SOC were 24 and 23 per cent, respectively in surface and sub-surface depths. These values indicate somewhat higher contribution of FA-C both towards SOM as well as SOC when compared with the contribution of HA-C. Like HA-C, the increasing levels of lantana addition from 10 to 30 t ha^{-1} were also found to increase FA-C content significantly and consistently over no lantana addition in both the soil depths. The per cent

Table 4.9 Long-term effect of lantana addition and fertilizer application on fulvic acid – carbon (g/100g of soil)

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	0.14	0.21	0.28	0.21
10	0.20	0.30	0.40	0.30
20	0.21	0.32	0.43	0.32
30	0.22	0.33	0.44	0.33
Mean	0.19	0.29	0.39	0.29
LSD = (0.05)	F=0.005	L=0.007	LxF=NS	
		(0.15 – 0.30 m)		
0	0.11	0.15	0.22	0.16
10	0.14	0.21	0.26	0.20
20	0.15	0.21	0.28	0.21
30	0.17	0.22	0.29	0.23
Mean	0.14	0.20	0.26	
LSD = (0.05)	F=0.004	L=0.006	LxF=NS	

increase being 43, 52 and 57 in surface depth and 25, 31 and 44 in sub-surface depth, respectively. Similarly, the fertilizer application at the rate of 66 and 100 per cent of the RD over its 33 per cent RD also increased FA-C significantly and consistently, the increase being 53 and 105 per cent in surface layer and 43 and 86 per cent in sub-surface layer. Like HA-C, the interaction between lantana addition and fertilizer application was not found significant on FA-C in any of the soil depths.

4.2.2 Soil Nitrogen, Phosphorus and Sulfur Pools

4.2.2.1 Active Pools

Nitrogen

Available nitrogen

The data regarding the effect of lantana addition and fertilizer application on available N have been given in Table 4.10. The available N varied from 327.6 kg ha^{-1} under 33 per cent of recommended fertilizer without lantana addition to a maximum value of 447.2 kg ha^{-1} under 100 per cent of RD of fertilizer along with 30 t ha^{-1} lantana addition with an average value of 391.4 kg ha^{-1} in surface soil depth. The corresponding values of available N content in sub-surface layer were from a minimum of 292.3 to a maximum of 388.2 kg ha^{-1} with an average value of 332.8 kg ha^{-1}. Thus, the per cent decrease in available-N was to the tune of 15 per cent in sub-surface layer when compared with surface layer. When the effect of lantana addition was studied irrespective of fertilizer application, it was found that the minimum amount of available-N was recorded under no lantana addition and maximum under 30 t ha^{-1} lantana

Table 4.10 Long-term effect of lantana addition and fertilizer application on soil available-N (kg-ha^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	327.6	333.3	336.4	332.4
10	376.3	392.3	408.0	392.2
20	395.4	410.5	425.4	410.4
30	413.7	430.6	447.2	430.5
Mean	378.3	391.7	404.3	
LSD = (0.05)	F=7.35	L=9.12	FxL=15.30	
		(0.15 – 0.30 m)		
0	292.3	295.4	296.1	294.6
10	312.7	326.4	340.2	326.4
20	328.4	342.2	355.4	342.0
30	350.4	366.4	388.2	368.3
Mean	321.0	332.6	345.0	
LSD = (0.05)	F=5.25	L=7.15	FxL=10.40	

addition. There was a significant and consistent increase in available-N with the successive increment of lantana addition in both the soil depths. Similarly, the fertilizer application at 66 and 100 per cent of RD also resulted into significant increase in available-N content over its 33 per cent dose in both the soil depths.

The interaction between lantana addition and fertilizer application was found significant in both the soil depths. The lantana addition from 10 to 30 t ha^{-1} increased available-N significantly under all the fertilizer levels. However, the application of fertilizer proved to be effective in increasing available-N content only when they were applied alongwith lantana addition in both soil depths. As far as fertilizer application in the absence of lantana addition was concerned, it was observed that there application did not influence the build up of available-N content in both the soil depths.

Water soluble – Nitrogen (WS-N)

The data pertaining to WS-N fraction was given in Table 4.11. A cursory look into this Table shows that WS-N, in general, ranged from a minimum value of 13.53 mg kg^{-1} under no lantana addition along with 33 per cent RD to a maximum value of 18.15 mg kg^{-1} under 30 t ha^{-1} lantana addition along with 100 per cent RD in surface depth. The corresponding values in sub-surface depth were 8.5 to 14.40 mg kg^{-1}, respectively. On an average basis, the decrease in WS-N in sub-surface depth was about 26 per cent when compared with surface depth. As far as contribution of WS-N towards available-N was concerned, it was observed that it constituted about 9 per cent of available-N in surface layer and 8 per cent in sub-surface depth. The increasing levels of lantana addition as well as fertilizer application increased WS-N significantly and consistently in both the soil depths.

Table 4.11 Long-term effect of lantana addition and fertilizer application on water soluble – N (mg kg^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	13.53	13.60	13.92	13.68
10	13.93	14.40	14.70	14.34
20	14.86	15.50	16.10	15.49
30	16.10	17.00	18.15	17.08
Mean	14.61	15.13	15.72	
LSD = (0.05)	F=0.18	L=0.21	FxL=NS	
		(0.15 – 0.30 m)		
0	8.59	9.00	9.30	8.96
10	10.40	10.70	10.81	10.64
20	11.50	12.00	12.40	11.97
30	12.39	13.10	14.40	13.30
Mean	10.72	11.20	11.73	
LSD = (0.05)	F=0.30	L=0.35	FxL=NS	

Soil microbial biomass – Nitrogen (SMB-N)

The content of SMB-N varied from 63.96 to 90.93 mg kg^{-1} in surface layer and 24.76 to 40.76 mg kg^{-1} in sub-surface layer (Table 4.12). The minimum content of SMB-N was observed under no lantana addition along with 33 per cent of RD and maximum under 30 t ha^{-1} lantana along with 100 per cent of RD. The average decrease in SMB-N in sub-surface was to the order of 42.1 mg kg^{-1} which was about 56 per cent. The lantana addition from 10 to 30 t ha^{-1} and fertilizer application from 66 to 100 per cent were observed to increase SMB-N significantly and consistently in both the soil depths. The average increase being 8, 19 and 31 per cent in surface layer and 27, 36 and 44 per cent in sub-surface layer with 10, 20 and 30 t ha^{-1} lantana addition over no lantana addition. Similarly, the increase under 66 and 100 per cent of RD was of the order of 5 and 10 per cent in surface depth and 12 and 24 per cent in sub-surface depth over 33 per cent of RD, respectively. In general, the contribution of SMB-N towards available-N was about 43 per cent in surface depth and 22 per cent in sub-surface depth. Comparing the contribution of WS-N and SMB-N towards available-N, it was observed that the contribution of SMB-N was about 5 times higher in comparison to WS-N.

The interaction between lantana addition and fertilizer application on SMB-N was found significant in both the soil depths. Lantana addition from 10 to 30 t ha^{-1} increased significantly and consistently SMB-N under all the levels of fertilizer application in the surface soil depth. However, in the sub-surface soil depth, the addition of lantana increased SMB-N significantly only over no lantana

Table 4.12 Long-term effect of lantana addition and fertilizer application on SMB-N (mg kg^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	63.96	65.43	66.63	65.34
10	66.56	69.63	74.63	70.27
20	74.66	78.43	80.56	77.88
30	80.56	85.10	90.93	85.53
Mean	71.43	74.64	78.18	
LSD = (0.05)	F=2.06	L=2.38	FxL=4.12	
		(0.15 – 0.30 m)		
0	24.76	25.90	26.76	25.81
10	27.40	33.03	37.63	32.68
20	30.93	35.23	39.16	35.10
30	33.73	37.20	40.76	37.23
Mean	29.21	32.84	36.07	
LSD = (0.05)	F=1.67	L=1.93	FxL=3.35	

addition under all the fertilizer levels. The fertilizer application at 66 and 100 per cent of its RD did not prove to be effective in influencing SMB-N significantly without lantana addition in both the soil depths. However, with lantana addition from 10 to 30 t ha^{-1} these two levels of fertilizer increased SMB-N significantly and consistently in sub-surface soil depth. By contrast, in surface layer, the application of 66 per cent of RD did not increase SMB-N under low levels of lantana addition (10 to 20 t ha^{-1}) but at 30 t ha^{-1}, it resulted into significant increase in SMB-N. As far as 100 per cent RD was concerned, it was found that there was increase in SMB-N under all the levels of lantana addition.

Phosphorus

Available phosphorus

The data with respect to available-P was given in Table 4.13. Like available-N, the minimum available P content was observed under no lantana addition along with 33 per cent of RD and maximum under 30 t ha^{-1} lantana addition along with 100 per cent of RD in both the soil depths. Irrespective of lantana levels and fertilizer application, the available P content was 21.14 kg ha^{-1} in surface layer and 10.0 kg ha^{-1} in sub-surface layer indicating a decrease of about 53 per cent. Irrespective of fertilizer application, the increasing levels of lantana addition increased available-P significantly and consistently in both the soil depths. The per cent increase being 13, 37 and 50 in surface layer and 9, 33 and 49 in sub-surface depth with 10, 20 and 30 t ha^{-1} over no lantana addition. Similarly, increasing fertilizer application also increased available-P significantly and consistently. The per cent increase being 8.0 and 7.5 in surface depth and 9.4 and 18.0 in sub-surface depth under 66 and 100 per cent of RD over 33 per cent of recommended fertilizer.

Table 4.13 Long-term effect of lantana addition and fertilizer application on soil available – P (kg ha^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	16.21	17.20	17.40	16.94
10	18.50	19.00	19.80	19.10
20	20.70	23.00	25.71	23.14
30	22.89	25.30	28.00	25.40
Mean	19.58	21.13	22.73	
LSD = (0.05)	F=0.93	L=1.16	FxL=2.06	
		(0.15 – 0.30 m)		
0	7.93	8.10	8.42	8.15
10	8.11	9.20	9.42	8.91
20	9.70	10.82	11.98	10.83
30	10.95	12.00	13.47	12.14
Mean	9.17	10.03	10.82	
LSD = (0.05)	F=0.52	L=0.50	FxL=NS	

The interaction between lantana addition and fertilizer application was found significant on available-P only in surface depth. Like available-N, the available-P was increased significantly with the addition of lantana from 10 to 30 t ha^{-1} under all the levels of fertilizer application. However, fertilizer application at 66 and 100 per cent of its RD increased available-P significantly when these levels were applied alongwith higher levels of lantana (20 to 30 t ha^{-1}). Under no lantana addition as well as with 10 t ha^{-1} lantana addition these two levels of fertilizer application did not influence available-P significantly when compared with 33 per cent of RD.

Water soluble phosphorus (WS-P)

The general, variations in WS-P were from 1.23 to 5.00 mg kg^{-1} in surface soil depth and from 0.70 to 2.77 mg kg^{-1} in sub-surface soil depth (Table 4.14). The minimum value was observed under no lantana addition alongwith 33 per cent of RD and a maximum with 30 t ha^{-1} lantana addition along with 100 per cent of RD in both the soil depths. Irrespective of lantana and fertilizer application, the average WS-P content was 4.25 mg kg^{-1} in surface layer and 2.21 mg kg^{-1} in sub-surface soil depth indicating almost 50 per cent reduction in WS-P in sub surface depth. The increasing levels of lantana addition and fertilizer application, increased WS-P in both the soil depths. The average WS-P content without lantana addition and irrespective of fertilizer levels was 1.30 mg kg^{-1} in surface depth which was increased to 3.57, 5.52 and 6.61 mg kg^{-1} under 10, 20 and 30 t ha^{-1} lantana addition. Similarly, the average WS-P content in sub-surface soil depth without lantana addition was 0.91 mg kg^{-1} which was

Table 4.14 Long-term effect of lantana addition and fertilizer application on water soluble-P (mg kg^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	1.23	1.33	1.33	1.30
10	2.50	3.56	4.65	3.57
20	4.12	5.50	6.95	5.52
30	5.80	6.92	7.10	6.61
Mean	3.41	4.33	5.00	
LSD = (0.05)	F=0.45	L=0.58	FxL=1.01	
		(0.15 – 0.30 m)		
0	0.70	0.92	1.10	0.91
10	1.11	1.80	2.25	1.72
20	1.96	2.49	3.12	2.52
30	2.82	3.70	4.60	3.71
Mean	1.65	2.23	2.77	
LSD = (0.05)	F=0.38	L=0.44	FxL=0.77	

increased to 1.72, 2.52 and 3.71 mg kg^{-1} under 10, 20 and 30 t ha^{-1} lantana addition. The application of 66 and 100 per cent of RD over its 33 per cent of RD increased WS-P by 28 and 48 per cent in surface layer and 35 and 68 per cent in sub-surface soil depth. On an average, WS-P constituted about 45 per cent of available-P in surface soil depth and about 50 per cent in sub-surface soil depth.

The interaction effect of lantana addition and fertilizer application was found significant in both the soil depths. The lantana addition increased WS-P significantly under all the levels of fertilizer application in both the soil depths whereas increasing fertilizer levels increased WS-P significantly only along with lantana addition. In the absence of lantana addition, fertilizer application did not influence WS-P significantly in both the soil depths.

Soil microbial biomass – Phosphorus (SMB-P)

Like different fractions of nitrogen, the minimum SMB-P content was observed without lantana addition alongwith 33 per cent of RD and maximum under 30 t ha^{-1} lantana addition alongwith 100 per cent of RD in both the soil depths (Table 4.15). The SMB-P ranged from 0.44 to 2.59 mg kg^{-1} in surface layer and 0.30 to 1.35 mg kg^{-1} in sub-surface layer. The average SMB-P was 1.38 mg kg^{-1} in surface layer in comparison to 0.88 mg kg^{-1} in sub-surface layer showing a decrease of about 36 per cent. Both, the addition of lantana as well as fertilizer application, resulted into significant increase in SMB-P in both the soil depths. The addition of 10, 20 and 30 t ha^{-1} lantana increased SMB-P by about 33, 105 and 100 per cent in surface depth and 40, 160 and 190 per cent in sub-surface depth. Similarly, fertilizer application at 66 and 100 per cent of RD over

Table 4.15 Long-term effect of lantana addition and fertilizer application on SMB-P (mg kg^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
	(0 – 0.15 m)			
0	0.44	0.70	1.23	0.79
10	0.71	1.00	1.45	1.05
20	1.23	1.56	2.17	1.65
30	1.57	1.95	2.59	2.04
Mean	0.99	1.30	1.86	
LSD = (0.05)	F=0.13	L=0.15	FxL=0.26	
	(0.15 – 0.30 m)			
0	0.30	0.43	0.59	0.44
10	0.49	0.56	0.80	0.62
20	1.10	1.19	1.26	1.18
30	1.21	1.28	1.35	1.28
Mean	0.78	0.87	1.00	
LSD = (0.05)	F=0.02	L=0.03	FxL=0.05	

its 33 per cent of RD increased this fraction of P by about 32 and 91 per cent in surface layer and 12 and 30 per cent in sub-surface layer. The SMB-P, in general, constituted 15 per cent of available-P in surface depth and about 20 per cent in sub-surface soil depth.

The interaction between lantana addition and fertilizr application was found significant in both the soil depths. All the levels of lantana addition under all the fertilizer application and all the levels of fertilizer applications under all the levels of lantana addition, increased SMB-P significantly in both the soil depths. It is noteworthy to indicate that SMB-P content under 100 per cent of RD without lantana addition was at par with 20 t ha^{-1} lantana addition alongwith 33 per cent of RD in surface layer.

Sulphur

Available sulphur

The range of available-S was from 10.10 kg ha^{-1} under 33 per cent of RD to 20.00 kg ha^{-1} under 30 t ha^{-1} lantana addition alongwith 100 per cent of RD in surface depth (Table 4.16). The corresponding values for these two treatments with respect to available-S were 6.50 and 19.25 kg ha^{-1} in sub-surface soil depth. Irrespective of lantana addition and fertilizer application, the average available-S content was 15.3 kg ha^{-1} in surface depth and 11.6 kg ha^{-1} in sub-surface depth indicating a decrease of about 24 per cent in sub-surface depth when compared with surface depth. The addition of lantana increased significantly and consistently available-S content in sub-surface depth whereas in surface depth each successive increment in lantana addition increased available-S content

Table 4.16 Long-term effect of lantana addition and fertilizer application on soil available – S (kg ha^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	10.10	10.50	10.85	10.48
10	12.20	14.00	16.50	14.23
20	14.50	17.00	19.30	16.93
30	17.00	19.50	22.00	19.50
Mean	13.45	15.25	17.16	
LSD = (0.05)	F=3.10	L=4.00	FxL=6.93	
		(0.15 – 0.30 m)		
0	6.50	6.61	6.72	6.61
10	8.71	10.40	12.45	10.52
20	10.80	13.00	15.10	12.97
30	13.53	16.50	19.25	16.43
Mean	9.89	11.63	13.38	
LSD = (0.05)	F=1.58	L=1.82	FxL=3.16	

significantly only over no lantana addition. Similarly, the application of fertilizer at 66 and 100 per cent of RD increased available-S content significantly and consistently in sub-surface layer but in surface depth, only 100 per cent of the RD resulted into significant increase in available-S over 33 per cent of RD.

The interaction between lantana addition and fertilizer application on available-S was found significant in both the soil depths. In surface depth, the application of fertilizer at 66 and 100 per cent of their dose did not affect available-S content without lantana addition, however, with lantana addition from 10 to 30 t ha^{-1}, while 66 per cent of RD was not capable of increasing available-S significantly, the 100 per cent of RD increased it significantly over its 33 per cent of RD. Lantana addition at the rate of 10 t ha^{-1} did not affect available-S significantly at any level of fertilizer application but its addition at the rate of 20 and 30 t ha^{-1} increased available-S significantly over its content under no lantana addition. The effect of fertilizer application on available-S was almost similar in surface depth as was observed in sub-surface depth. However, the effect of lantana addition was slightly modified in sub-surface depth under 66 and 100 per cent of RD. All levels of lantana addition increased available-S significantly and consistently under 66 and 100 per cent of RD whereas under 33 per cent of RD, only 20 and 30 t ha^{-1} lantana addition increased available-S content and that to only over no lantana addition.

Water soluble sulphur (WS-S)

Irrespective of lantana addition and fertilizer application, the average WS-S content was 1.76 mg kg^{-1} in surface depth and 1.34 mg kg^{-1} in sub-surface depth. Water soluble S contributed about 26 per cent towards available-S in both the soil depths (Table 4.17). The average reduction in WS-S in sub-surface depth in comparison to surface depth was about 24 per cent.

Table 4.17 Long-term effect of lantana addition and fertilizer application on water soluble – S (mg kg^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	1.50	1.53	1.57	1.53
10	1.63	1.65	1.70	1.66
20	1.75	1.86	1.95	1.85
30	1.88	1.98	2.10	1.99
Mean	1.69	1.76	1.83	
LSD = (0.05)	F=0.02	L=0.03	FxL=NS	
		(0.15 – 0.30 m)		
0	0.96	1.10	1.15	1.07
10	1.22	1.32	1.38	1.31
20	1.37	1.48	1.52	1.46
30	1.46	1.53	1.60	1.53
Mean	1.25	1.36	1.41	
LSD = (0.05)	F=0.03	L=0.04	FxL=NS	

The interaction between lantana addition and fertilizer application was not found significant in any of the soil depth. However, the addition of lantana as well as fertilizer application influenced WS-S significantly in both the soil depths. Increasing levels of lantana addition irrespective of fertilizer application and increasing levels of fertilizer application irrespective of lantana addition, increased WS-S significantly and consistently.

Soil microbial biomass – Sulphur (SMB-S)

The data pertaining to SMB-S was given in Table 4.18. A deep insight into this Table indicates that like available and WS-S contents, the SMB-S ranged from a minimum value of 4.03 mg kg^{-1} without lantana addition and 33 per cent of RD to a maximum value of 6.85 mg kg^{-1} under 30 t ha^{-1} lantana addition and 100 percent of RD in surface depth. The respective values for SMB-S under these two treatments in sub-surface soil depth were 2.26 and 4.26 mg kg^{-1}. Irrespective of lantana and fertilizer addition, the average SMB-S was 5.34 and 4.29 mg kg^{-1} in surface and sub-surface soil depth, respectively. This indicates about 20 per cent decrease in SMB-S in sub-surface depth when compared to surface depth. It is interesting to note that about 2/3rd of available-S in the present soil constituted the SMB-S in both the soil depths. Like available-S, increasing levels of lantana addition and fertilizer application resulted into significant build up of SMB-S in both the soil depths. The increase being about 19, 35 and 47 per cent in surface depth and 30, 55 and 74 per cent in sub-surface depth under 10, 20 and 30 t ha^{-1} lantana addition over no lantana addition, respectively. Similarly, the build up in SMB-S under 66 and 100 per cent of RD over its 33 per cent of RD was to the tune of 11 and 22 per cent in surface depth and 16 and 29 per cent in sub-surface soil depth.

Table 4.18 Long-term effect of lantana addition and fertilizer application on SMB-S (mg kg^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	4.03	4.23	4.55	4.27
10	4.56	5.10	5.58	5.08
20	5.06	5.80	6.34	5.74
30	5.67	6.22	6.85	6.25
Mean	4.83	5.34	5.95	
LSD = (0.05)	F=0.26	L=0.31	FxL=0.53	
		(0.15 – 0.30 m)		
0	2.26	2.46	2.67	2.46
10	2.70	3.20	3.66	3.19
20	3.26	3.85	4.30	3.80
30	3.72	4.28	4.78	4.26
Mean	2.99	3.45	3.85	
LSD = (0.05)	F=0.21	L=0.24	FxL=0.42	

The interaction effect of lantana addition and fertilizer application on SMB-S was found significant in both the soil depths. The lantana addition from 10 to 30 t ha^{-1} increased significantly and consistently SMB-S under all the levels of fertilizer application in both the soil depths. However, fertilizer application at the rate of 66 and 100 per cent of RD increased SMB-S only in the presence of lantana addition, whereas, in the absence of lantana addition, these two fertilizer levels did not increase SMB-S significantly over its 33 per cent dose.

4.2.2.2 Passive Pools

Nitrogen and sulphur

The effect of lantana addition and fertilizer application on passive pools of N and S was not found significant in any of the soil depths, hence the main effect of lantana addition as well as fertilizer application on these two parameters was given in Table 4.19 and detailed data have been appended in Appendix-III to VI. The average HA-N content was observed to be 1.10 g/100g of soil in surface depth and 0.71 g/100g of soil in sub-surface depth, respectively, indicating a decrease of about 36 per cent in sub-surface depth. The increasing levels of fertilizer application were not found to affect HA-N significantly in any of the soil depths. However, the addition of lantana from 10 to 30 t ha^{-1} increased this fraction of N significantly and consistently in both the soil depths. The absolute increase under 10, 20 and 30 t ha^{-1} lantana addition in comparison to no lantana was 0.06, 0.39 and 0.54 in surface and 0.04, 0.12 and 0.19 in sub-surface depth, respectively. The average content of FA-N was about 0.35 g/100g of soil in surface depth and 0.26 g/100g of soil in sub-surface depth indicating a decrease

of about 26 per cent in sub-surface depth. When FA-N was compared with HA-N, it was found that FA-N content was about 3 times less in surface depth and 2.75 per cent less in sub-surface soil depth. The increasing levels of lantana as well as fertilizer increased FA-N significantly and consistently in both the soil depths.

Table 4.19 Long-term effect of lantana addition and fertilizer application on passive pools of nitrogen and sulphur (g/100g of soil)

	Soil depth							
	0-0.15 m				0.15-0.30 m			
	Humic acid-N	Fulvic acid-N	Humic acid-S	Fulvic acid-S	Humic acid-N	Fulvic acid-N	Humic acid-S	Fulvic acid-S
Lantana addition (t ha^{-1})								
0	0.85	0.29	0.22	0.15*	0.62	0.23	0.12	0.10
10	0.91	0.33	0.36	0.22	0.66	0.25	0.16	0.12
20	1.24	0.36	0.45	0.27	0.74	0.27	0.21	0.16
30	1.39	0.41	0.52	0.32	0.81	0.29	0.24	0.19
LSD = (0.05)	0.06	0.13	0.03	0.02	0.03	0.01	0.02	0.02
Fertilizer levels (% of RD)								
33	1.06	0.33	0.35	0.20	0.68	0.25	0.17	0.13
66	1.09	0.35	0.39	0.24	0.71	0.26	0.18	0.14
100	1.14	0.37	0.43	0.29	0.74	0.27	0.20	0.16
LSD = (0.05)	NS	0.10	0.02	0.01	NS	0.01	0.01	0.01

Like HA-N, the HA-S content was also increased significantly and consistently both with increasing levels of lantana as well as fertilizer application in both the soil depths. The minimum HA-S content was observed under no lantana addition and maximum under 30 t ha^{-1} lantana addition. Similarly, lowest HA-S content was recorded under 33 per cent of RD and highest under 100 per cent of RD. Similar to HA-S, lantana addition from 10 to 30 t ha^{-1} and fertilizer application from 66 to 100 per cent of RD, increased FA-S content significantly and consistently in both the soil depths. The lowest content was observed under no lantana and highest under 30 t ha^{-1} lantana addition in both the soil depths. The same trend was observed with increasing fertilizer levels. On an average, when FA-S content was compared with HA-S, it was observed that FA-S was about 1.6 and 1.3 times less in surface and subsurface soil depths, respectively.

4.2.3 Microbial Count

The effect of long-term lantana addition and fertilizer application on microbial count in respect of bacteria, fungi and actinomycetes was studied in the present investigation.

Bacteria

A study of Table 4.20 indicates that lantana addition irrespective of fertilizer application and fertilizer application irrespective of lantana addition increased bacterial count significantly and consistently in both the soil depths. The bacterial population under 0, 10, 20 and 30 t ha^{-1} lantana addition was found to the tune of 14.88, 21.66, 41.77 and 55.11 cfux10^5 g/soil in surface depth and 9.55, 14.78, 27.33 and 38.55 cfux10^5 g/soil in sub-surface depth, respectively.

Table 4.20 Long-term effect of lantana addition and fertilizer application on microbial count-bacteria (cfux10^5 g/soil)

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	12.00	14.66	18.00	14.88
10	17.00	22.00	26.00	21.66
20	32.66	43.66	49.00	41.77
30	47.66	55.33	62.33	55.11
Mean	27.33	33.91	38.83	
LSD = (0.05)	F=2.70	L=3.12	FxL=5.41	
		(0.15 – 0.30 m)		
0	7.33	9.33	12.00	9.55
10	13.00	13.33	18.00	14.78
20	23.00	26.00	33.00	27.33
30	32.66	37.66	45.33	38.55
Mean	19.00	21.58	27.08	
LSD = (0.05)	F=NS	L=4.43	FxL=NS	

Similarly, the bacterial population under 33, 66 and 100 per cent of RD was of the order of 27.33, 33.91 and 38.83 cfux10^5 g/soil in surface depth and 19.00, 21.58 and 27.08 cfux10^5 g/soil in sub-surface soil, respectively. In general, the bacterial population was found about 1.3 times less in sub-surface soil depth in comparison to surface soil depth. The interaction between lantana addition and fertilizer application on bacterial population was found significant only in surface soil depth. The application of 66 per cent of RD did not influence bacterial population either without lantana addition or with 10 t ha^{-1} lantana addition. However, the addition of 100 per cent of RD increased bacterial population significantly over 33 per cent of the RD even under these two lantana additions. Conversely, the addition of 66 and 100 per cent of RD over 33 per cent of RD increased bacterial population at higher levels of lantana addition (20 and 30 t ha^{-1}. The addition of lantana at the rate of 10 t ha^{-1} did not increase bacterial population significantly under 33 per cent of RD. However, this level of lantana resulted into significant increase in bacterial population under higher levels of fertilizer application (66 and 100 per cent of the RD). The addition of 20 and 30 t ha^{-1} lantana increased bacterial population significantly and consistently under all the levels of fertilizer application.

Fungi

The fungi population in the surface soils ranged from 35.66 cfux10^5 g/soil under no lantana addition and 33 per cent of RD to 59.66 cfux10^5 g/soil under 30 t ha^{-1} lantana addition alongwith 100 per cent of RD (Table 4.21). The corresponding values under these two treatment combinations in sub-surface depth were 15.00 and 37.66 cfux10^5 g/soil. The average value for population of

Table 4.21 Long-term effect of lantana addition and fertilizer application on microbial count-fungi (cfux10^5 g/soil)

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
	(0 – 0.15 m)			
0	35.66	37.33	46.33	39.77
10	39.33	43.00	52.66	45.00
20	45.66	51.33	56.33	51.11
30	51.33	55.66	59.66	55.55
Mean	43.00	46.58	53.75	
LSD = (0.05)	F=2.74	L=3.16	FxL=NS	
	(0.15 – 0.30 m)			
0	15.00	24.00	28.33	22.44
10	21.33	27.66	32.00	27.00
20	26.33	32.33	35.00	31.22
30	29.33	33.33	37.66	33.44
Mean	23.00	29.33	33.25	
LSD = (0.05)	F=2.19	L=2.53	FxL=NS	

fungi in surface and sub-surface depth was 47.8 and 28.5 cfux10^5 g/soil, respectively, indicating clearly the decrease of about 1.32 times which was almost the same as was observed for the bacterial population. Individually, both lantana addition and fertilizer application increased fungi population significantly in both the soil depths, the increase being 13, 29 and 40 per cent in surface depth and 20, 29 and 40 per cent in surface depth under 10, 20 and 30 t ha^{-1} lantana addition in comparison to no lantana addition, respectively. Similarly, the per cent increase in fungi population under 66 and 100 per cent of RD in comparison to its 33 per cent of RD was 9 and 25 in surface and 28 and 45 in sub-surface depth, respectively.

The interaction between lantana addition and fertilizer application was not found significant on fungi population in any of the soil depth.

Actinomycetes

Actinomycetes population ranged from a minimum value of 13.33 to a maximum value of 44.33 cfux10^5 g/soil in surface layer and from 9.66 to 29.75 cfux10^5 g/soil in sub-surface layer (Table 4.22). The average actinomycetes population irrespective of lantana addition and fertilizer application was found to be 26.28 cfux10^5 g/soil in surface depth and 18.50 cfux10^5 g/soil in sub-surface depth indicating slightly a higher decrease (1.42 per cent) in actinomycetes population in comparison to bacteria and fungi population. In general, lantana addition and fertilizer application increased actinomycetes population significantly and consistently in both the soil depths.

The interaction between lantana addition and fertilizer application on actinomycetes population was also found significant in both the soil depths. Without lantana application, only 100 per cent of RD increased actinomycetes

Table 4.22 Long-term effect of lantana addition and fertilizer application on microbial count – actinomycetes (cfux10^5 g/soil)

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	13.33	16.33	19.66	16.44
10	17.00	23.33	28.90	21.78
20	21.00	32.33	39.33	30.89
30	26.33	37.33	44.33	36.00
Mean	19.42	27.33	32.08	
LSD = (0.05)	F=2.77	L=3.20	FxL=5.55	
		(0.15 – 0.30 m)		
0	9.66	11.66	15.33	12.22
10	11.33	16.50	20.85	16.23
20	15.33	21.55	27.00	21.29
30	19.00	24.00	29.75	24.25
Mean	13.83	18.43	23.02	
LSD = (0.05)	F=2.15	L=3.00	FxL=4.31	

population over its 33 per cent of RD. However, when lantana was applied from 10 to 30 t ha^{-1}, the application of both 66 and 100 per cent of RD increased actinomycetes population significantly in both the soil depths. Similarly, at lower levels of fertilizer application (33 per cent of RD), the addition of lantana at the rate of 10 t ha^{-1} was not found to be capable of increasing actinomycetes population significantly whereas 20 and 30 t ha^{-1} lantana addition resulted into significant increase in actinomycetes population under this level of fertilizer application. Contrary to this, the lantana addition right from 10 to 30 t ha^{-1} increased actinomycetes population significantly and consistently under 66 and 100 per cent of RD in both the soil depths.

4.3 Chemical Properties

Soil samples collected from two soil depths were analyzed for their pH, available N, P, K, S, Fe, Mn, Cu and Zn. The data with respect to available-N, P and S has already been presented under the section soil N, P and S pools. In this section the data regarding soil pH, available-K, Fe, Mn, Cu and Zn has been presented.

Soil pH

The soil pH ranged from a minimum value of 5.49 under no lantana addition alongwith 33 per cent of RD to a maximum value of 5.68 under 30 t ha^{-1} lantana addition along with 100 per cent of RD in surface depth (Table 4.23). The corresponding values for these two treatments in sub-surface depth were 5.83 and 6.12, respectively. In general, the soil pH was higher in sub-surface soil depth in comparison to surface depth. As far as the effect of lantana addition and

Table 4.23 Long-term effect of lantana addition and fertilizer application on soil pH

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
	(0 – 0.15 m)			
0	5.49	5.49	5.46	5.48
10	5.56	5.59	5.60	5.58
20	5.57	5.60	5.63	5.60
30	5.64	5.68	5.68	5.67
Mean	5.56	5.59	5.59	
LSD = (0.05)	F=NS	L=0.08	FxL=NS	
	(0.15 – 0.30 m)			
0	5.83	5.81	5.83	5.82
10	5.90	5.90	5.92	5.91
20	5.94	5.96	6.03	5.98
30	5.98	5.98	6.12	6.03
Mean	5.91	5.91	5.96	
LSD = (0.05)	F=NS	L=0.09	FxL=NS	

fertilizer application individually and their interaction on soil pH was concerned, it was found that application of fertilizers did not influence soil pH significantly in any of the soil depths. Similarly, the interaction between lantana addition and fertilizer application was also not found significant on soil pH in any of the soil depths. However, the additions of lantana significantly influenced soil pH in both the soil depths. A study of Table 4.23 indicates that increasing levels of lantana addition from 10 to 30 t ha^{-1} increased significantly soil pH in both the soil depths in comparison to no lantana addition. The absolute increase in soil pH was from 5.48 to 5.67 in surface depth and from 5.82 to 6.03 in sub-surface soil depth.

Available potassium

Like soil pH, the interaction between lantana addition and fertilizer application was also not found significant on available-K content in both the soil depths (Table 4.24). However, lantana addition and fertilizer application individually increased significantly and consistently the available-K in surface soil depth whereas in sub-surface soil depth fertilizer application even was not significant in influencing available-K content. As far as lantana addition was concerned, it was found that its addition from 10 to 30 t ha^{-1} increased available-K content significantly and consistently in both the soil depths. The per cent increase being 10, 17 and 33 in surface depth and 10, 17 and 26 in sub-surface depth under 10, 20 and 30 t ha^{-1} lantana addition, respectively when compared with no lantana addition. Similarly, the application of fertilizer from 66 to 100 per cent of RD also increased available-K content significantly and consistently over its 33 per cent of dose.

Table 4.24 Long-term effect of lantana addition and fertilizer application on soil available-K (kg ha^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
	(0 – 0.15 m)			
0	231.4	251.6	278.9	253.9
10	240.4	284.9	312.0	279.1
20	261.7	263.0	362.1	295.6
30	309.4	335.0	365.8	336.7
Mean	260.7	283.6	329.7	
LSD = (0.05)	F=17.4	L=20.9	FxL=NS	
	(0.15 – 0.30 m)			
0	215.7	215.7	221.0	217.5
10	234.3	234.3	248.9	239.2
20	251.1	256.4	257.4	254.9
30	264.4	272.7	285.2	274.1
Mean	241.4	244.8	253.1	
LSD = (0.05)	F=NS	L=17.6	FxL=NS	

DTPA-Fe

The interaction effect of lantana addition and fertilizer application on DTPA-Fe was not found significant in any of the soil depth (Table 4.25). However, individually, the addition of lantana as well as fertilizer application influenced DTPA-Fe significantly in both the soil depths. The addition of lantana while increased DTPA-Fe significantly and consistently in both the soil depths, the application of fertilizers has significant and negative effect on DTPA-Fe. The absolute values of DTPA-Fe increased from 8.13 mg kg^{-1} without lantana addition to 9.80, 11.98 and 14.12 mg kg^{-1} under 10, 20 and 30 t ha^{-1} lantana addition, respectively, in surface soil depth. The respective values in sub-surface soil depth were from 7.81 to 9.77, 11.73 and 13.95 mg kg^{-1}. Conversely, the increasing doses of fertilizers from 66 to 100 per cent of RD decreased DTPA-Fe significantly and consistently in both the soil depths, the decrease being 4.5 and 7.0 per cent in surface depth and 3.9 and 7.4 per cent in sub-surface soil depth when compared with 33 per cent of RD.

DTPA-Mn

Like DTPA-Fe, the interaction effect of lantana addition and fertilizer application was also not found significant on DTPA-Mn in any of the soil depths (Table 4.26). However, increasing levels of lantana addition increased DTPA-Mn significantly and consistently in both the soil depths. The per cent increase being 32, 53 and 88 in surface depth and 17, 38 and 58 in sub-surface depth with 10, 20 and 30 t ha^{-1} lantana addition when compared with no lantana addition. Contrary to this, the increasing levels of fertilizer application decreased DTPA-Mn

Table 4.25 Long-term effect of lantana addition and fertilizer application on DTPA – Fe (mg kg^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	8.43	8.00	7.95	8.13
10	10.00	9.75	9.65	9.80
20	12.50	11.95	11.50	11.98
30	14.85	14.00	13.50	14.12
Mean	11.45	10.93	10.65	
LSD = (0.05)	F=0.48	L=0.64	FxL=NS	
		(0.15 – 0.30 m)		
0	8.00	7.80	7.64	7.81
10	10.10	9.70	9.50	9.77
20	12.20	11.70	11.30	11.73
30	14.65	14.00	13.20	13.95
Mean	11.24	10.80	10.41	
LSD = (0.05)	F=0.20	L=0.23	FxL=NS	

Table 4.26 Long-term effect of lantana addition and fertilizer application on DTPA-Mn (mg kg^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
	(0 – 0.15 m)			
0	8.40	7.25	6.95	7.53
10	9.98	9.95	9.80	9.91
20	12.53	11.00	10.98	11.50
30	14.35	14.00	14.00	14.12
Mean	11.32	10.55	10.43	
LSD = (0.05)	F=0.60	L=0.68	FxL=NS	
	(0.15 – 0.30 m)			
0	7.35	7.00	6.85	7.07
10	8.40	8.35	8.00	8.25
20	9.95	9.70	9.52	9.72
30	11.50	11.00	10.90	11.13
Mean	9.30	9.01	8.82	
LSD = (0.05)	F=0.28	L=0.35	FxL=NS	

significantly in both the soil depths when compared with 33 per cent of the RD. However, there was not significant difference on DTPA-Mn between 66 and 100 per cent of RD in both the soil depths. The average DTPA-Mn in surface and sub-surface soil depth was 10.71 and 9.14 mg kg^{-1}, respectively, indicating a decrease of about 15 per cent in sub-surface soil depth.

DTPA-Cu

Data regarding DTPA-Cu as affected by lantana addition and fertilizer application was given in Table 4.27. Like DTPA-Fe and Mn, the effect of fertilizer application as well as the interaction between lantana addition and fertilizer application was not found significant on DTPA-Cu in any of the soil depths. However, as far as the addition of lantana was concerned, it was observed that its addition from 10 to 30 t ha^{-1} increased DTPA-Cu significantly and consistently in both the soil depths. The average content of DTPA-Cu was 1.11 mg kg^{-1} in surface depth and 0.92 mg kg^{-1} in sub-surface depth, respectively.

DTPA-Zn

In general, the range of variation in DTPA-Zn was from 0.60 mg kg^{-1} without lantana addition along with 33 per cent of RD to 0.65 mg kg^{-1} with 30 t ha^{-1} lantana addition along with 100 per cent of RD in surface soil depth (Table 4.28). The corresponding range of variation in DTPA-Zn was from 0.52 to 0.59 mg kg^{-1} under these two respective treatments in sub-surface soil depth. The addition of lantana from 10 to 30 t ha^{-1} increased significantly DTPA-Zn in both the soil depths. In contrast, the application of fertilizers from 66 to 100 per cent of

Table 4.27 Long-term effect of lantana addition and fertilizer application on DTPA-Cu (mg kg^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	0.96	0.97	0.98	0.97
10	1.05	1.07	1.06	1.06
20	1.17	1.15	1.18	1.17
30	1.24	1.23	1.23	1.23
Mean	1.11	1.11	1.11	
LSD = (0.05)	F=NS	L=0.06	FxL=NS	
		(0.15 – 0.30 m)		
0	0.80	0.77	0.78	0.78
10	0.89	0.88	0.89	0.89
20	0.97	0.96	0.98	0.97
30	1.04	1.05	1.07	1.05
Mean	0.93	0.92	0.93	
LSD = (0.05)	F=NS	L=0.05	FxL=NS	

Table 4.28 Long-term effect of lantana addition and fertilizer application on DTPA-Zn (mg kg^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	0.60	0.58	0.56	0.58
10	0.63	0.60	0.58	0.60
20	0.68	0.64	0.63	0.65
30	0.71	0.66	0.65	0.67
Mean	0.66	0.62	0.60	
LSD = (0.05)	F=0.02	L=0.03	FxL=NS	
		(0.15 – 0.30 m)		
0	0.52	0.50	0.48	0.50
10	0.56	0.54	0.52	0.54
20	0.59	0.57	0.55	0.57
30	0.64	0.61	0.59	0.61
Mean	0.58	0.56	0.54	
LSD = (0.05)	F=0.02	L=0.03	FxL=NS	

RD decreased DTPA-Zn significantly over its 33 per cent dose in both the soil depths. In general, the DTPA-Zn was about 1.12 times less in sub-surface soil depth in comparison to surface depth.

4.4 Carbon Sequestration and SOM Dynamics

Periodic changes in C-sequestration

The data on the effect of lantana addition and fertilizer application on periodic changes in C stock have been presented in Table 4.29. The soil C stock was worked out at two years interval in 1990, 1992, 1994, 1996, 1998, 2000 and 2004 on original soil mass basis. The original soil mass of 1 hectare furrow slice was 1875 Mg at 1.25 Mgm^{-3} bulk density (BD). The continuous addition of lantana and fertilizer application has lead to change physical environment of soil as revealed by BD of soils (Table 4.1). The decline in BD results in increased volume of furrow soil. Under such circumstances determination of C stock results in its under estimation. The BD under different treatments were estimated in 2004, hence these BD values were used to work out actual C stock. Accordingly in 2004, the C stock in various treatments was worked out on original soil mass basis as well as on the basis of estimated BD values. A reference to data in Table (4.29) revealed that continuous addition of lantana since last 17 years increased C stock right from 1992-2004. Similarly, the increase in fertilizer application also resulted in an increase in C stock. However, the increase was much higher under lantana addition in comparison to fertilizer addition.

Irrespective of fertilizer application, the average increase in C stock on original soil mass basis under 10, 20 and 30 t ha^{-1} lantana addition in comparison to no lantana addition was 1.69, 4.00 and 5.31 Mg ha^{-1} in 1990, 2.87, 4.75 and

Table 4.29 Effect of long term addition of lantana and chemical fertilizer application on periodic changes on SOC stock (Mg ha^{-1}) in 0-0.15 m soil depth

Treatments	SOC stock (Mg ha^{-1})								
	1990 (On original soil mass basis)	1992 (On original soil mass basis)	1994 (On original soil mass basis)	1996 (On original soil mass basis)	1998 (On original soil mass basis)	2000 (On original soil mass basis)	2004		ΔC stock ha^{-1} yr^{-1}
							Based on BD values	On original soil mass basis	
M_0 F33%	16.12	16.50	16.68	16.68	16.68	16.87	16.97	17.25	0.01
M_0 F66%	16.68	16.87	16.87	16.87	16.87	17.25	17.24	17.81	0.03
M_0 F100%	17.25	17.25	17.43	17.43	17.43	17.43	17.28	18.00	0.06
M_{10} F33%	18.00	18.93	20.43	21.18	21.37	21.75	20.53	22.12	0.24
M_{10} F66%	18.37	19.87	21.18	21.56	22.12	22.12	21.40	23.06	0.28
M_{10} F100%	18.75	20.43	21.75	22.12	22.50	22.68	22.11	23.62	0.31
M_{20} F33%	20.43	21.18	22.12	22.31	23.06	23.25	21.47	24.18	0.34
M_{20} F66%	20.62	21.56	22.68	23.25	23.62	24.00	22.27	25.31	0.38
M_{20} F100%	21.00	22.12	22.87	23.81	24.18	24.37	22.60	25.68	0.41
M_{30} F33%	21.56	22.31	22.50	23.43	24.18	24.18	22.93	26.06	0.41
M_{30} F66%	22.12	22.87	23.43	23.81	24.37	24.93	23.10	26.25	0.44
M_{30} F100%	22.31	23.06	23.62	24.18	24.75	25.31	23.23	26.62	0.46

Initial (1988) = 16.5

*Original soil mass of 1875 Mg ha^{-1} at 1.25 Mgm^{-3} bulk density in 1988 was considered for working out soil carbon stock at two years interval

5.88 Mg ha^{-1} in 1992, 4.13, 5.57 and 6.19 Mg ha^{-1} in 1994, 4.63, 6.13 and 6.82 in 1996, 5.00, 6.63 and 7.44 Mg ha^{-1} in 1998, 5.00, 6.69 and 7.44 Mg ha^{-1} in 1998, 5.00, 6.69 and 7.63 Mg ha^{-1} in 2000, 5.24, 7.34 and 8.62 Mg ha^{-1} in 2004, respectively. This clearly indicates that with advancement of time there was a regular increase in C-stock with the addition of lantana. It is pertinent to indicate here that minimum C stock build up was observed under no lantana addition along with 33 per cent of RD. Under this treatment, for a certain period of time, there was at all no build up in C stock. The data in Table 4.29 further indicates that as the levels of lantana addition and fertilizer application increased, the build up in C stock also increased. The maximum increase in C stock build up was observed under 30 t ha^{-1} lantana addition along with 100 per cent of RD in every year. The continuous addition of lantana at the rate of 10, 20 and 30 t ha^{-1} resulted in gain of about 1.50, 7.12 and 9.18 Mg ha^{-1} C when compared with C stock in 1988 on original soil mass basis, respectively. In general, the values for C stock was lower based on actual BD values when compared with original soil mass basis in the year 2004 under all the treatments. The build-up in C stock ha^{-1} yr^{-1} (ΔC) was also calculated by summing up all the C-stock values during the year 1990, 1992, 1994, 1996, 1998, 2000 and 2004 on original soil mass basis and average C stock was calculated by dividing this sum by seven. From this, the initial C stock of 16.5 Mg ha^{-1} was substracted and remaining value was divided by seventeen to find the C stock Mg ha^{-1} yr^{-1}. Irrespective of fertilizer application, the addition of lantana at the rate of 10, 20 and 30 t ha^{-1} increased C stock build up by 0.25, 0.35 and 0.41 Mg C ha^{-1} yr^{-1} when compared with no

lantana addition. The fertilizer application at the rate of 66 and 100 per cent of RD also resulted in an increase in C stock buildup when compared with 33 per cent of its dose. However, the increase was quite less in comparison to increase with lantana addition and amounted only to 0.03 and 0.07 Mg C ha^{-1} yr^{-1} under 66 and 100 per cent of RD, respectively.

Soil organic matter (SOM) dynamics

On the basis of average content of 52.5 per cent of OC in lantana on dry weight basis, the total OC added over the last 17 years was calculated. The total build up in SOM over the last 17 years and OM retained in soil and its relative distribution in different active and passive pools was also calculated. The data regarding these parameters are given in Table 4.30 for 0-0.30 m soil depth. Similarly, the relative distribution of OC in different active and passive pools in 0-0.15 and 0.15-0.30 m on the basis of total SOM retained in 0-0.30 m was also given in Table 4.31.

The total carbon added by the addition of 10, 20 and 30 t ha^{-1} over the last 17 years was 32.13, 64.26 and 96.39 t ha^{-1}, respectively (Table 4.30). The respective amount of C retained under these three levels of lantana addition was found to be 16.2, 9.6 and 7.8 per cent when OC in 0-0.30 m soil depth was taken together. This soil OC retained was further converted to SOM content and then the percentage of SOM retained under different levels of lantana were calculated by substracting the amount of OM present in control plot. The percentage of OM retained in soils under 10, 20 and 30 t ha^{-1} lantana addition was about 28, 15 and 12 per cent, respectively. A study of Table 4.30 indicates that C retained as a

Table 4.30 Long term effect of lantana addition on carbon sequestration and SOM dynamics in 0-0.30 m soil depth (t ha^{-1})

Lantana levels	C-added through lantana over 17 years	SOC after 17 yrs of lantana addition on soil mass basis	SOM after 17 yrs of lantana addition	SOM retained in soil	Distribution of C in active and passive pools											
					Active pools							Passive pools				
					WS-OC		WS-CHO		SMB-C		Total	HA-C		FA-C		Total
					Observed	Retained	Observed	Retained	Observed	Retained		Observed	Retained	Observed	Retained	
0	-	31.69	54.63	-	0.19	-	2.20	-	1.15	-	-	7.84	-	8.28	-	-
10	32.13	36.90	63.62	8.99 (27.98)	0.32	0.13 (1.45)	2.46	0.26 (2.89)	1.34	0.19 (2.11)	0.58 (6.45)	10.59	2.75 (30.59)	11.29	3.01 (33.48)	5.76 (64.07)
20	64.26	37.83	65.27	10.64 (15.00)	0.44	0.25 (2.35)	2.77	0.57 (5.36)	1.53	0.38 (3.57)	1.20 (11.28)	10.94	3.10 (29.14)	11.61	3.33 (31.30)	6.43 (60.44)
30	96.39	39.23	67.63	13.00 (12.45)	0.47	0.38 (2.92)	3.00	0.80 (6.15)	1.81	0.66 (5.08)	1.84 (14.15)	11.32	3.48 (26.77)	12.18	3.90 (30.00)	7.38 (56.77)
Mean	64.26	36.41	62.79	10.88 (18.48)	0.36	0.25 (2.24)	2.61	0.54 (4.80)	1.46	0.412 (3.59)	1.21 (10.63)	10.17	3.11 (28.83)	10.84	3.41 (31.59)	6.52 (60.43)

*Data in parentheses indicates per cent contribution towards retained SOM

percentage of retained SOM in both active and passive pools together constituted about 71, 72 and 71 under 10, 20 and 30 t ha^{-1} lantana addition, respectively. Further, the distribution of total OM retained (in both the soil depths together) under different levels of lantana addition was studied in different active and passive pools.

The major portion of OM retained in soil was observed to be present in passive pools. The percentage of OC in active pool as a fraction of retained OM in 0-0.15 m and 0.15-0.30 m soil depth together was about 6, 11 and 14 under 10, 20 and 30 t ha^{-1} lantana addition, respectively. This indicates that the retention of C in active pools increased with increasing levels of lantana. Out of average of about 11 per cent C retained in active pool as a fraction of SOM, the maximum was retained in WS-CHO (5 per cent) followed by SMB-C (4 per cent) and minimum in WS-OC (2 per cent). Increasing levels of lantana increased retention of C under all the three active pools in 0-0.30 m soil depth. As far as passive pools of SOC retained in soils were concerned, it was found that on an average, the maximum retention was observed in FA-C (about 32 per cent) and minimum in HA-C (about 29 per cent). Unlike active pools of SOC, the C retained in HA and FA fraction decreased with increasing levels of lantana from 10 to 30 t ha^{-1}.

The retention of OC in different active and passive pools in 0-0.30 m soil depth was further studied to see their distribution in 0-0.15 and 0.15-0.30 m soil depth as a fraction of total OM retained in two soil depths together. Out of the average retention of OC (71 per cent) in both active and passive pools in 0-0.30

m soil depth, about 48 per cent OC was retained in surface depth and 23 per cent in sub-surface soil depth indicating a decrease of about 50 per cent in lower soil depth (Table 4.31). Further, out of 48 per cent of OC in active and passive pool in surface depth, the major portion was in passive pool (42 per cent) and only a small fraction was present in active pool (6 per cent). The same trend of OC distribution among active and passive pools was observed in sub-surface soil depths also. Like OM retention in 0-0.30 m soil depth, the highest retention was observed in passive pools and lowest in active pools in 0-0.15 and 0.15-0.30 m soil depths also. The C retained in sub-surface soil depth in FA and HA-C together was about 2.2 times less when compared with surface depth. Similarly, the OC retained in active pool in 0.15-0.30 m soil depth was about 1.3 times less when compared with 0-0.15 m soil depth. Out of total C as a fraction of total SOM retained in 0-0.30 m soil depth in WS-OC (2.24), WS-CHO (4.80 per cent) and SMB-C (3.59 per cent), 1.36, 2.48 and 2.12 per cent was retained in surface layer. Similarly, out of about 32 and 29 per cent OC in FA and HA-C retained in 0-0.30 m soil depth, about 22 and 20 per cent of these passive pool fractions were retained in surface layer. The corresponding values for these fractions were about 10 and 9 per cent in sub-surface soil depth, respectively.

Like 0-0.30 m soil depth, the C retained in passive pools (HA + FA-C) decreased with increasing levels of lantana addition whereas the retention in active pools (WS-OC + WS-CHO + SMB-C) increased in both the soil depths. In general, the maximum retention of added OC as a fraction of soil OM retained in soil was observed in HA-C among passive pools and WS-CHO in active pools in both the soil depths.

Table 4.31 Long term effect of lantana addition on carbon sequestration and SOM dynamics (t ha^{-1})

Lantana levels	C-added through lantana over 17 years	SOC after 17 yrs of lantana addition on soil mass basis	SOM after 17 yrs of lantana addition	SOM retained in soil	Distribution of C in active and passive pools (0-0.15 m)											
					Active pools							Passive pools				
					WS-OC		WS-CHO		SMB-C		Total	HA-C		FA-C		Total
					Observed	Retained	Observed	Retained	Observed	Retained		Observed	Retained	Observed	Retained	
0	-	17.06	29.4	-	0.11	-	1.22	-	0.69	-	-	4.48	-	4.70	-	-
10	32.13	21.28	36.7	7.3 (22.7)	0.19	0.08 (0.89)	1.32	0.10 (1.11)	0.80	0.11 (1.22)	0.29 (3.22)	6.43	1.95 (21.69)	6.80	2.10 (23.35)	4.05 (45.04)
20	64.26	22.11	38.1	8.7 (13.5)	0.26	0.15 (1.41)	1.54	0.32 (3.01)	0.91	0.22 (2.07)	0.69 (6.49)	6.68	2.20 (20.68)	7.05	2.35 (22.09)	4.55 (42.77)
30	96.39	23.10	39.8	10.4 (10.8)	0.34	0.23 (1.77)	1.65	0.43 (3.31)	1.09	0.40 (3.08)	1.06 (8.16)	6.78	2.30 (17.69)	7.30	2.60 (20.00)	4.90 (37.61)
Mean		20.89	36.0	8.8 (15.7)	0.23	0.15 (1.36)	1.43	0.28 (2.48)	0.87	0.24 (2.12)	0.68 (5.96)	6.09	2.15 (20.02)	6.46	2.35 (21.81)	4.50 (41.83

*Data in parentheses indicate per cent contribution towards retained SOM

Contd../-

Lantana levels	C-added through lantana over 17 years	SOC after 17 yrs of lantana addition on soil mass basis	SOM after 17 yrs of lantana addition	SOM retained in soil	Distribution of C in active and passive pools (0.15-0.30 m)											
					Active pools							Passive pools				
					WS-OC		WS-CHO		SMB-C		Total	HA-C		FA-C		Total
					Observed	Retained	Observed	Retained	Observed	Retained		Observed	Retained	Observed	Retained	
0	-	14.63	25.2	-	0.08	-	0.99	-	0.46	-	-	3.36	-	3.58	-	-
10		15.62	26.9	1.7 (5.3)	0.13	0.05 (0.56)	1.14	0.15 (1.67)	0.55	0.09 (1.00)	0.29 (3.23)	4.16	0.80 (8.90)	4.49	0.91 (10.12)	1.71 (19.02)
20		15.75	27.2	2.0 (3.1)	0.18	0.10 (0.94)	1.23	0.24 (2.26)	0.63	0.17 (1.60)	0.51 (4.80)	4.26	0.90 (8.46)	4.56	0.98 (9.21)	1.88 (17.67)
30		16.13	27.8	2.6 (2.7)	0.23	0.15 (1.15)	1.35	0.36 (2.77)	0.72	0.26 (2.00)	0.77 (5.92)	4.54	1.18 (9.08)	4.88	1.30 (10.00)	2.48 (17.08)
Mean		15.53	26.7	2.1 (3.7)	0.62	0.10 (0.88)	1.18	0.25 (2.23)	0.59	0.17 (1.53)	0.52 (4.65)	4.08	0.96 (8.81)	4.38	1.06 (9.78)	2.02 (18.59)

*Data in parentheses indicate per cent contribution towards retained SOM

4.5 Yield and Nutrient Uptake

4.5.1 Grain and Straw Yield of Rice and Wheat

RICE

Grain yield

The data with respect to grain yield of rice as affected by lantana addition and fertilizer application are given in Table 4.32. A study of this Table indicates that rice grain yield in general, varied from 2.35 to 4.08 Mg ha^{-1} during *Kharif* 2004 and from 2.32 to 4.25 Mg ha^{-1} during 2005. During both the years, the lowest yield was recorded with 33 per cent of RD without lantana addition and highest with 100 per cent of RD along with 30 t ha^{-1} lantana in 2005 and 20 t ha^{-1} lantana in 2004, respectively. Irrespective of fertilizer application, the lantana addition increased rice grain yield significantly and consistently during both the years. The average increase with 10, 20 and 30 t ha^{-1} lantana addition over no lantana addition was 8, 28 and 32 per cent during 2004 and 10, 33 and 37 per cent during 2005, respectively.

Similar to lantana addition, the fertilizer application from 66 to 100 per cent of RD over its 33 per cent dose, increased rice grain yield significantly and consistently during both the years. The average increase was 27 and 31 per cent during 2004 and 26 and 37 per cent during 2005, respectively.

The interaction between lantana addition and fertilizer application was found significant on rice grain yield during both years of experimentation. A further study of Table 4.32 reveals that lantana addition from 10 to 30 t ha^{-1} increased rice grain yield significantly and consistently when added under 33 per

Table 4.32 Long-term effect of lantana addition and fertilizer application on rice grain yield (Mg ha^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	2.35	3.12	3.37	2.95
10	2.62	3.36	3.60	3.19
20	3.10	4.10	4.10	3.77
30	3.50	4.05	4.08	3.88
Mean	2.89	3.66	3.79	
LSD = (0.05)	F=0.12	L=0.11	FxL=0.22	
		(0.15 – 0.30 m)		
0	2.32	2.90	3.45	2.89
10	2.58	3.21	3.73	3.17
20	3.12	4.18	4.21	3.84
30	3.43	4.16	4.25	3.95
Mean	2.86	3.61	3.91	
LSD = (0.05)	F=0.93	L=1.07	FxL=0.18	

cent of RD. However, under 66 and 100 per cent of RD while 10 t ha^{-1} lantana application increased rice grain yield significantly, the further increase in its addition from 20 to 30 t ha^{-1} did not affect rice grain yield significantly during both the years. This indicates that the higher application of lantana (20 to 30 t ha^{-1}) under higher level of fertilizer application was not capable of increasing rice grain yield significantly. Similarly, the fertilizer application from 66 to 100 per cent of RD increased rice grain yield significantly and consistently over its 33 per cent RD only under 10 t ha^{-1} lantana addition during both the years. However, when these higher doses of fertilizers were applied under higher levels of lantana addition (20 to 30 t ha^{-1}), they were not capable of increasing rice grain yield significantly in both the years.

Straw yield

The rice straw yield, in general, ranged from 3.42 to 6.57 Mg ha^{-1} during 2004 and from 3.39 to 6.60 Mg ha^{-1} during 2005, respectively (Table 4.33). Like grain yield, the lowest straw yield of rice was recorded under the treatment of 33 per cent of RD with no lantana addition and highest under 100 per cent of RD along with 30 t ha^{-1} lantana addition.

Irrespective of fertilizer application, lantana addition, in general, increased straw yield of rice significantly and consistently during both the years. The average increase in straw yield was 10, 32 and 38 per cent during 2004 and 13, 37 and 40 per cent during 2005 under 10, 20 and 30 t ha^{-1} lantana when compared with no lantana addition, respectively. Similarly, the fertilizer application, in general, also produced significantly and consistently higher rice

Table 4.33 Long-term effect of lantana addition and fertilizer application on rice straw yield (Mg ha^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	3.42	4.67	5.02	4.37
10	3.67	4.96	5.81	4.81
20	4.60	6.28	6.40	5.76
30	5.10	6.46	6.57	6.04
Mean	4.19	5.59	5.95	
LSD = (0.05)	F=0.14	L=0.16	FxL=0.28	
		(0.15 – 0.30 m)		
0	3.39	4.56	5.33	4.43
10	4.28	4.74	5.93	4.98
20	5.20	6.43	6.53	6.05
30	5.66	6.40	6.60	6.22
Mean	4.63	5.53	6.09	
LSD = (0.05)	F=0.12	L=0.14	FxL=0.25	

straw yield. The per cent increase in straw yield was 33 and 42 during 2004 and 20 and 32 during 2005 under 66 and 100 per cent of RD over its 33 per cent dose, respectively.

The interaction between lantana addition and fertilizer application was found significant during both the years of experimentation. Like rice grain yield, the addition of lantana from 10 to 30 t ha^{-1} increased rice straw yield significantly and consistently when added under 33 per cent of RD during both the years. However, under 66 and 100 per cent of RD the lantana addition only upto 20 t ha^{-1} resulted into significant increase in straw yield of rice whereas further increase in its addition to 30 t ha^{-1} did not influence the rice straw yield significantly during both the years under these two levels of fertilizer application. The fertilizer application at 66 to 100 per cent also increased rice straw yield significantly over its 33 per cent dose both in absence and in the presence of lower level of lantana addition (10 t ha^{-1}) during both the years. Contrary to this, under higher levels of lantana addition (20 to 30 t ha^{-1}), only 66 per cent of RD increased straw yield significantly over its 33 per cent dose whereas further increase to its application to 100 per cent did not influence rice straw yield significantly when compared with 66 per cent of the RD during both the years.

WHEAT

Grain yield

Data pertaining to the effect of lantana addition and fertilizer application of wheat grain yield are given in Table 4.34. A reference to this Table indicates that wheat grain yield, in general, varied from 2.60 to 3.77 Mg ha^{-1} in

Table 4.34 Long-term effect of lantana addition and fertilizer application on wheat grain yield (Mg ha^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	2.60	2.96	3.34	2.97
10	2.96	3.35	3.69	3.33
20	3.33	3.70	3.78	3.60
30	3.68	3.71	3.77	3.72
Mean	3.14	3.43	3.64	
LSD = (0.05)	F=0.17	L=0.19	FxL=0.34	
		(0.15 – 0.30 m)		
0	2.87	3.10	3.45	3.14
10	3.10	3.43	3.66	3.40
20	3.41	3.74	3.86	3.67
30	3.66	3.69	3.78	3.71
Mean	3.26	3.49	3.68	
LSD = (0.05)	F=0.12	L=0.15	FxL=0.23	

the year 2004-05 and from 2.87 to 3.78 Mg ha^{-1} during 2005-06. In both the years, the lowest yield was observed under no lantana addition along with 33 per cent of RD and highest under 20 t ha^{-1} lantana addition along with 100 per cent of RD.

Irrespective of fertilizer application, the lantana addition in general increased wheat grain yield significantly in both the years. The average increase was 12, 21 and 25 during 2004-05 and 8, 17 and 18 per cent during the year 2005-06 with the addition of 10, 20 and 30 t ha^{-1} lantana in comparison to no lantana addition, respectively. Similarly, irrespective of lantana addition, increasing doses of fertilizer application also increased wheat grain yield significantly and consistently during both the years. The average increase was 9 and 16 per cent in 2004-05 and 7 and 13 per cent in 2005-06 under 66 and 100 per cent of RD over 33 per cent of RD.

The interaction between lantana addition and fertilizer application was found significant during both years. A reference to Table 4.34 indicates that when effect of lantana addition was studied under different levels of fertilizer application, it was found that under 33 per cent of RD lantana addition from 10 to 30 t ha^{-1} increased wheat grain yield during both the years. However, under 66 and 100 per cent of RD lantana addition only upto 20 t ha^{-1} was found to be capable of increasing wheat grain yield significantly and consistently, whereas, further increase in lantana addition to 30 t ha^{-1} did not improve wheat grain yield significantly over its 20 t ha^{-1} addition under these two fertilizer levels in both the years. As far as effect of fertilizer application was concerned, it was observed

that application of 66 and 100 per cent of RD increased wheat grain significantly and consistently in absence as well as in the presence of only lower levels of lantana addition (10 t ha^{-1}). However in presence of higher levels of lantana (20 to 30 t ha^{-1}), only the application of 66 per cent of RD was found to increase wheat grain yield significantly over its 33 per cent of RD, whereas further increase in fertilizer application to 100 per cent of RD did not bring about any significant improvement in wheat grain yield over 66 per cent of RD during both the years.

Straw yield

Like wheat grain yield, the lowest yield of wheat straw was recorded under no lantana addition along with 33 per cent of RD and highest under 20 t ha^{-1} lantana addition along with 100 per cent of RD during both the years of experimentation (Table 4.35). The range of variation in wheat straw yield was from 3.35 to 5.83 Mg ha^{-1} in 2004-05 and from 3.83 to 5.88 Mg ha^{-1} during 2005-06.

Like wheat grain yield, the increasing levels of lantana addition irrespective of fertilizer application increased wheat straw yield significantly and consistently during both the years of study. The per cent increase being 20, 37 and 47 during 2004-05 and 15, 28 and 32 during 2005-06 under 10, 20 and 30 t ha^{-1} lantana addition in comparison to no lantana addition, respectively. Similarly, the increasing levels of fertilizers, irrespective of lantana levels, also increased wheat straw yield significantly and consistently during both the years. The increase being 15 and 23 per cent in 2004-05 and 14 and 20 per cent in 2005-06 under 66 and 100 per cent of RD in comparison to 33 per cent of RD.

Table 4.35 Long-term effect of lantana addition and fertilizer application on wheat straw yield (Mg ha^{-1})

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
	(0 – 0.15 m)			
0	3.35	3.96	4.40	3.90
10	3.99	4.75	5.23	4.66
20	4.52	5.60	5.91	5.34
30	5.49	5.60	5.83	5.64
Mean	4.34	4.98	5.34	
LSD = (0.05)	F=0.17	L=0.21	FxL=0.39	
	(0.15 – 0.30 m)			
0	3.83	4.36	4.92	4.37
10	4.40	5.06	5.66	5.04
20	4.96	5.79	5.99	5.58
30	5.46	5.98	5.88	5.77
Mean	4.66	5.30	5.61	
LSD = (0.05)	F=0.24	L=0.29	FxL=0.51	

The interaction between lantana addition and fertilizer application was found significant on wheat straw yield during both the years. When the effect of lantana addition was studied under different fertilizer levels, it was observed that lantana addition only upto 20 t ha^{-1} addition increased wheat straw yield significantly and consistently under all the levels of fertilizer application, whereas further increase in its addition to 30 t ha^{-1} did not increase wheat straw yield significantly over its 20 t ha^{-1} addition under all the levels of fertilizer application. As far as the effect of increasing levels of fertilizer application was concerned, it was found that application of 66 per cent of the RD increased wheat straw yield significantly and consistently in the absence as well as in the presence of lower level of lantana addition (10 t ha^{-1}) during both the years. However, under higher levels of lantana addition (20 to 30 t ha^{-1}), the fertilizer application only at the rate of 66 per cent increased wheat straw yield significantly over its 33 per cent of dose. The further increase in application of fertilizer to 100 per cent did not improve wheat straw yield significantly over its 66 per cent dose during both the years of experimentation.

4.5.2 Nutrient Uptake by Rice and Wheat

The interaction between lantana and fertilizer levels was not found significant on the uptake N, P and S either by rice or by wheat, hence, only the main effects of these two factors are given in this section for rice and wheat separately.

RICE

The data pertaining to the effect of lantana addition and fertilizer application on the uptake of N, P and S by rice during *Kharif* 2004 and 2005 are presented in Table 4.36. A study of the data in this Table indicates that addition of lantana from 10 to 30 t ha^{-1} brought about significant increase in the uptake of

Table 4.36 Long-term effect of lantana addition and fertilizer application on total N, P and S (kg ha^{-1}) uptake by rice

Treatments	*Kharif* 2004			*Kharif* 2005		
	N	P	S	N	P	S
Lantana addition (t ha^{-1})						
0	69.20	15.79	9.42	68.79	15.57	9.40
10	75.40	20.72	12.29	73.86	20.53	11.78
20	83.90	23.26	14.32	88.04	25.47	15.09
30	88.14	25.54	15.61	94.68	28.35	17.06
LSD=(0.05)	3.99	1.27	0.91	2.41	2.68	0.52
Fertilizer application (% of RD)						
33	70.94	15.53	9.93	69.19	16.03	10.02
66	79.36	23.48	13.64	84.14	27.33	14.28
100	85.09	24.65	15.91	90.29	29.87	17.70
LSD=(0.05)	3.46	1.09	0.78	2.09	2.28	0.45

N, P and S by rice over the control during both the years of experimentation. The increase being 9.0, 21.2 and 27.4 per cent in N; 31.2, 47.4 and 61.7 per cent in P and 30.5, 52.0 and 65.7 per cent in S under 10, 20 and 30 t ha^{-1} lantana addition during the year 2004. The respective per cent increase in the uptake of these nutrients during 2005 was 7.4, 28.0 and 37.6 in N; 31.8, 63.6 and 82.1 in P; and 25.3, 60.5 and 81.5 in S, respectively.

Similarly, the application of fertilizer from 66 to 100 per cent of RD significantly increased the uptake of N, P and S by rice crop during both the years. The per cent increase in N, P and S uptake at 66 and 100 per cent dose over its 33 per cent dose was 11.9 and 19.9, 51.2 and 58.7 and 37.4 and 60.2 during 2004, respectively. The corresponding increase in 2005 was 21.6 and 30.5 in N; 70.5 and 86.3 in P and 42.5 and 76.6 in S, respectively.

WHEAT

The data pertaining to N, P and S uptake by wheat during *Rabi* 2004-05 and 2005-06 as influenced by lantana addition and fertilizer application are presented in Table 4.37. A critical examination of the data in this Table indicates that like grain yield of wheat, addition of lantana at the rate of 10, 20 and 30 t ha^{-1} also exhibited significant increase in N, P and S uptake over the control during both the years of experimentation. The increase being 19.4, 26.7 and 32.7 in N; 8.3, 12.9 and 18.4 in P; 19.2, 42.4 and 51.4 per cent in S. A further examination of the data in this table revels that fertilizer application from 66 to 100 per cent of RD significantly increased the uptake of N, P and S by wheat crop during both the years of study when compared with 33 per cent of RD. The per cent increase

Table 4.37 Long-term effect of lantana addition and fertilizer application on total N, P and S (kg ha^{-1}) uptake by wheat

Treatments	*Rabi* 2004-05			*Rabi* 2005-06		
	N	P	S	N	P	S
Lantana addition (t ha^{-1})						
0	62.37	13.50	6.91	73.66	13.01	6.90
10	74.48	14.62	8.24	86.10	14.28	8.28
20	79.02	15.24	9.84	92.41	15.47	10.30
30	82.79	15.99	10.46	97.16	16.39	10.76
LSD=(0.05)	3.74	0.51	0.49	2.36	0.91	0.31
Fertilizer application (% of RD)						
33	65.68	13.96	7.31	75.94	13.98	7.71
66	74.28	14.50	9.50	87.32	14.82	9.53
100	78.03	15.70	10.33	91.23	15.67	10.38
LSD=(0.05)	3.24	0.44	0.42	2.01	0.79	0.44

in N, P and S uptake at 66 and 100 per cent of fertilizer dose over its 33 per cent dose was 13.1 and 18.8, 3.9 and 12.5 and 29.9 and 41.3 during 2004-05. The corresponding values for increase in N, P and S uptake during 2005-06 under 66 and 100 per cent of RD were 14.9 and 20.1, 6.0 and 12.1 and 23.6 and 34.6, respectively.

4.6 Relationship between SOM Pools, Nutrient's Supply and Crop Productivity

An attempt has been made to work out the relationship between active (WS-CHO, WS-OC, SMB-C); slow (C bound to different aggregate size fractions of soils) and passive (HA-C and FA-C) pools of SOM and rice and wheat grain yield as well as nutrient supply (N, P and S). These relationships have been worked out both by simple coefficient of correlations 'r' and stepwise regression data.

RICE

Relationship of SOM pools with nutrient supply and crop productivity

The values for coefficient of correlations 'r' and step wise regression data between SOM pools and nutrient supply and crop productivity has been given in Table 4.38. The nutrient supply as well as rice yield was significantly and positively correlated with all the SOM pools except one slow pool of SOM (2-1 mm). Among different active pools, WS-CHO had the highest coefficient of correlations 'r' with rice grain yield and nutrient supply in terms of N, P and S, which was followed by WS-OC. Among slow pools, the C bound to particles less than 0.25 mm was found to have highest coefficient of correlations 'r' with rice

grain yield as well as with the supply of N and S. However, in case of P supply, the highest coefficient of correlation 'r' was observed with particles of more than 2 mm. The passive pools of SOM (HA-C and FA-C) have almost similar coefficient of correlations 'r' with nutrient supply as well as with grain yield of rice.

Table 4.38 Coefficient of correlation 'r' between SOM pools, rice grain yield and nutrient's supply

SOM pools	Grain yield	Nutrient supply		
		N	P	S
Active pools				
WS-OC	0.8394**	0.9415**	0.8385**	0.8414**
WS-CHO	0.8929**	0.9579**	0.8961**	0.9128**
SMB-C	0.6648**	0.8665**	0.7634**	0.6529**
Slow pools				
> 2 mm-C	0.5538**	0.7426**	0.7132**	0.5551**
2-1 mm-C	0.0963	0.0521	0.0169	0.1778
1-0.5 mm-C	0.4063*	0.5601**	0.5519**	0.4257*
0.5-0.25 mm-C	0.5688**	0.6522**	0.5192**	0.4658*
< 0.25 mm-C	0.6342**	0.8079**	0.6716**	0.6407**
Passive pools				
HA-C	0.8516**	0.6239**	0.6454**	0.9135**
FA-C	0.8477**	0.6241**	0.6462**	0.9127**

* Significant at 5% level of significance
** Significant at 1% level of significance

To study the relative contribution of different carbon pools towards rice grain yield and nutrient supply, the linear step wise regressions were computed and the equations obtained are given in Table 4.39. From the order of relative importance of the independent variables, it is evident that the most important variable contributing to the total variations in the regression of rice grain yield and uptake of N, P and S was WS-CHO. The R^2 values indicate that about 80, 92, 80 and 83 per cent of total variations, respectively, in rice grain yield, N uptake, P uptake and S uptake were attributable to WS-CHO. The second stage of step wise regression analysis indicated that SMB-C was the second most important organic fraction contributing to the total variations in rice grain yield, total P and S uptake whereas in case of N uptake, the second most important variable was found to be WS-OC. The relative contribution of SMB-C was found to the tune of about 7, 1 and 11 per cent in case of rice yield and N, S uptake, respectively.

Relationship of nutrient's pool with nutrient supply and crop productivity

The coefficient of correlations 'r' between different pools of nutrients and nutrient supply (N, P and S) and rice grain yield are given in Table 4.40. A study of this Table indicates that all the active pools of N, P, S as well as passive pools of N and S were correlated significantly and positively with N, P and S uptake and rice grain yield.

Like soil organic pools, to assess the relative contribution of the various nutrient pools to nutrient supply and crop productivity, linear step wise regressions were computed and are given in Table 4.41. A study of this Table reveals that among different pools of nutrients, SMB-P was the most important

Table 4.39 Step-wise regression data for the relationship between rice grain yield, nutrient supply, Y, and SOM pools

Dependent variable (Y)	Step No.	Variable on which Y is regressed	R^2	ΔR^2	F value
Grain yield	1.	WS-CHO	0.7973	-	133.8
	2.	WS-CHO, SMB-C	0.8648	0.0675	105.5
	3.	WS-CHO,SMB-C, 2-1mm-C	0.8727	0.0079	73.1
	4.	WS-CHO, SMB-C, 2-1 mm-C, 0.5-0.25 mm-C	0.8899	0.0172	62.6
	5.	WS-CHO, SMB-C, 2-1 mm-C, 0.5-0.25 mm-C, 1-0.5 mm-C	0.8975	0.0076	52.5
	6.	WS-CHO, SMB-C, 2-1 mm-C, 0.5-0.25 mm-C, 1-0.5 mm-C, WS-OC	0.9119	0.0144	50.0
	7.	WS-CHO, SMB-C, 2-1 mm-C, 0.5-0.25 mm-C, 1-0.5 mm-C, WS-OC, HA-C	0.9158	0.0039	52.5
	8.	WS-CHO, SMB-C, 2-1 mm-C, 0.5-0.25 mm-C, 1-0.5 mm-C, WS-OC, HA-C, FA-C	0.9193	0.0035	55.1
Total N uptake	1.	WS-CHO	0.9176	-	378.7
	2.	WS-CHO, WS-OC	0.9436	0.026	276.1
	3.	WS-CHO, WS-OC, 0.5-0.25 mm-C	0.9514	0.0078	208.6
	4.	WS-CHO, WS-OC, 0.5-0.25 mm-C, 2-1 mm-C	0.9590	0.0076	181.4
	5.	WS-CHO, WS-OC, 0.5-0.25 mm-C, 2-1 mm-C, HA-C	0.9605	0.0015	146.1
Total P uptake	1.	WS-CHO	0.8031	-	138.7
	2.	WS-CHO, SMB-C	0.8132	0.0101	71.8
	3.	WS-CHO, SMB-C, < 0.25 mm-C	0.8214	0.0082	49.0
	4.	WS-CHO, SMB-C, < 0.25 mm-C, WS-OC	0.8325	0.0111	38.5
	5.	WS-CHO, SMB-C, < 0.25 mm-C, WS-OC, 2-1 mm-C	0.8530	0.0205	34.8
	6.	WS-CHO, SMB-C, < 0.25 mm-C, WS-OC, 2-1 mm-C, 0.5-0.25 mm-C	0.8597	0.0067	29.6
	7.	WS-CHO, SMB-C, < 0.25 mm-C, WS-OC, 2-1 mm-C, 0.5-0.25 mm-C, HA-C	0.8694	0.0097	26.6
	8.	WS-CHO, SMB-C, < 0.25 mm-C, WS-OC, 2-1 mm-C, 0.5-0.25 mm-C, HA-C, FA-C	0.8765	0.0071	24.0
Total S uptake	1.	WS-CHO	0.8344	-	171.4
	2.	WS-CHO, SMB-C	0.9437	0.1093	276.7
	3.	WS-CHO, SMB-C, 1-0.5 mm-C	0.9477	0.004	193.4
	4.	WS-CHO, SMB-C, 1-0.5 mm-C, 0.25 mm-C	0.9571	0.0094	172.9
	5.	WS-CHO, SMB-C, 1-0.5 mm-C, 0.25 mm-C, HA-C	0.9593	0.0022	141.5
	6.	WS-CHO, SMB-C, 1-0.5 mm-C, 0.25 mm-C, HA-C, WS-OC	0.9612	0.0019	119.8
	7.	WS-CHO, SMB-C, 1-0.5 mm-C, 0.25 mm-C, HA-C, WS-OC, FA-C	0.9630	0.0018	104.2

Table 4.40 Coefficient of correlation 'r' between nutrient pools, rice grain yield and nutrient's supply

SOM pools	Grain yield	Nutrient's supply		
		N	P	S
Active pools				
Available N	0.7908	0.9126	0.8699	0.8079
SMB-N	0.8155	0.9041	0.8053	0.8197
WS-N	0.7951	0.8941	0.8181	0.8054
Available P	0.8442	0.9203	0.8317	0.8539
SMB-P	0.9071	0.8971	0.7978	0.9388
WS-P	0.8435	0.9228	0.8648	0.8403
Available S	0.8619	0.9192	0.8635	0.8853
SMB-S	0.8697	0.8936	0.8685	0.8869
WS-S	0.7669	0.8617	0.7519	0.7755
Passive pools				
HA-N	0.7982	0.9379	0.7883	0.8223
FA-N	0.7659	0.9020	0.7947	0.7140
HA-S	0.8636	0.9248	0.8488	0.8755
FA-S	0.8084	0.8559	0.7767	0.8089

All the values are significant at 1% level of significance

Table 4.41 Step-wise regression data for the relationship between rice grain yield, nutrient supply, Y, and nutrient pools

Dependent variable (Y)	Step No.	Variable on which Y is regressed	R^2	ΔR^2	F value
Grain yield	1.	SMB-P	0.8227	-	157.8
	2.	SMB-P, SMB-N	0.8354	0.0127	83.7
	3.	SMB-P, SMB-N, SMB-S	0.8562	0.0208	63.5
	4.	SMB-P, SMB-N, SMB-S, WS-P	0.8597	0.0035	47.5
	5.	SMB-P, SMB-N, SMB-S, WS-P, AV-N	0.8801	0.0204	44.0
Total N uptake	1.	AV-N	0.8796	-	248.3
	2.	AV-N, SMB-P	0.9316	0.052	224.9
	3.	AV-N, SMB-P, SMB-S	0.9308	0.0072	163.6
	4.	AV-N, SMB-P, SMB-S, SMB-N	0.9506	0.0118	149.1
	5.	AV-N, SMB-P, SMB-S, SMB-N, AV-S	0.9542	0.0036	124.9
	6.	AV-N, SMB-P, SMB-S, SMB-N, AV-S, HA-S	0.9575	0.0033	108.9
	7.	AV-N, SMB-P, SMB-S, SMB-N, AV-S, HA-S, AV-P	0.9588	0.0013	93.1
Total P uptake	1.	AV-P	0.7569	-	105.9
	2.	AV-P, SMB-N	0.7870	0.0301	60.9
	3.	AV-P, SMB-N, SMB-S	0.7950	0.008	41.4
	4.	AV-P, SMB-N, SMB-S. SMB-P	0.8014	0.0064	31.3
	5.	AV-P, SMB-N, SMB-S. SMB-P, WS-P	0.8094	0.008	25.5
Total S uptake	1.	SMB-S	0.8814	-	252.6
	2.	SMB-S, SMB-P	0.9137	0.0323	174.8
	3.	SMB-S, SMB-P, AV-S	0.9284	0.0147	138.3
	4.	SMB-S, SMB-P, AV-S, WS-N	0.9369	0.0085	114.9
	5.	SMB-S, SMB-P, AV-S, WS-N, WS-P	0.9399	0.003	93.9
	6.	SMB-S, SMB-P, AV-S, WS-N, WS-P, SMB-N	0.9542	0.0143	100.7
	7.	SMB-S, SMB-P, AV-S, WS-N, WS-P, SMB-N, AV-P	0.9570	0.0028	
	8.	SMB-S, SMB-P, AV-S, WS-N, WS-P, SMB-N, AV-P, AV-N	0.9582	0.0012	77.3

fraction contributing to the variation of rice grain yield. The total variation in grain yield explained by this factor was about 82 per cent. Similarly, available-N, available-P and SMB-S were the most important fractions contributing to the total variations in total uptake of N, P and S, respectively. The relative contribution of these factors were found to the tune of about 88, 76 and 88 per cent, respectively. The second most important nutrient pool from the point of view of rice grain yield was SMB-N. Similarly the second most important nutrient pools with respect to N, P and S uptake was SMB-P, SMB-N and SMB-P respectively. The relative contribution of these pools towards N, P and S uptake was about 5, 3 and 3 per cent, respectively. The third most important nutrient pool in case of rice grain yield and N and P uptake was found to be SMB-S, whereas in case of S uptake, it was available-S.

WHEAT

Relationship of SOM pools with nutrient supply and crop productivity

An attempt has also been made to find out the relationship between different SOM pools and nutrient supply and crop productivity. The coefficient of correlations 'r' for these relationships are given in Table 4.42. An insight into the data in this Table reveals that all the SOM pools (active, slow and passive) were found to be correlated significantly and positively with nutrient supply and wheat grain yield except one slow pool (2-1 mm) which was not found to be correlated significantly either with nutrient supply or with wheat grain yield. Like the relationship between different SOM pools and nutrient supply and crop yield of rice, the highest coefficient of correlation 'r' was observed with WS-CHO in case

of active pools of SOM. As far as slow pools of SOM are concerned, the SOM associated with less than 0.25 mm was found to have highest coefficient of correlations 'r' with nutrient supply and wheat grain yield. Among passive pools, HA-C was found to have higher coefficient of correlations 'r' with nutrient supply and grain yield in comparison to FA-C.

Table 4.42 Coefficient of correlation 'r' between SOM pools, wheat grain yield and nutrient's supply

SOM pools	Grain yield	Nutrient supply		
		N	P	S
Active pools				
WS-OC	0.87010	0.81476	0.84905	0.84143
WS-CHO	0.88978	0.81005	0.87278	0.87285
SMB-C	0.73005	0.62465	0.74825	0.73569
Slow pools				
> 2 mm	0.69635	0.72668	0.65417	0.68491
2-1 mm	0.18159*	0.07766*	0.16916*	0.54951*
1-0.5 mm	0.56559	0.60028	0.51029	0.52565
0.5-0.25 mm	0.58015	0.65893	0.50171	0.60065
< 0.25 mm	0.72578	0.66183	0.70566	0.72686
Passive pools				
HA-C	0.81810	0.74452	0.71079	0.69326
FA-C	0.80967	0.72664	0.69409	0.68227

* Values are non-significant at 5% level of significance

The linear step wise regression equations were also computed between different SOM pools and nutrient supply and crop productivity to find out the relative contribution of different SOM pools. A study of Table 4.43 indicates that like nutrient supply to rice and its yield, the most important SOM pool contributing to the variations in wheat grain yield and uptake of N, P and S was WS-CHO. The R^2 values for this SOM pool reveals that about 79, 66, 76 and 76 per cent variations in wheat grain yield and uptake of N, P and S, respectively, were explained only by WS-CHO. Like rice, the second most important SOM pool contributing for the variations in wheat grain and uptake of P and S was SMB-C, whereas for total N uptake, it was WS-OC. The total variations explained by WS-CHO and SMB-C were abut 84, 78 and 79 per cent in grain yield and P and S uptake. Similarly, the total variation explained by WS-CHO and WS-OC was about 74 per cent in case of total N uptake by wheat crop.

Relationship of nutrient's pool with nutrient supply and crop productivity

A study of Table 4.44 reveals that all the nutrient pools (active and passive) were significantly and positively correlated with nutrient supply (N, P, S) and wheat productivity. Among active pools of nutrients, SMB-P had the highest coefficient of correlations 'r' (0.896) with wheat grain yield followed by SMB-S (0.881). Similarly, SMB-S had the highest coefficient of correlation (0.838) followed by WS-P (0.831) in case of N uptake, whereas available-P (0.859) and SMB-N (0.820) had the highest and second highest coefficient of correlation in case of P uptake. In case of S uptake, WS-P was found to have highest coefficient of correlation (0.876) followed by available-S (0.857). In case of passive pools, HA-S was found to bear highest coefficient of correlations 'r' with nutrient supply (N, P, S) and wheat productivity.

Table 4.43 Step-wise regression data for the relationship between wheat grain yield, nutrient supply, Y, and SOM pools

Dependent variable (Y)	Step No.	Variable on which Y is regressed	R^2	ΔR^2	F value
Grain yield	1.	WS-CHO	0.7917	-	129.2
	2.	WS-CHO, SMB-C	0.8363	0.0446	84.3
	3.	WS-CHO, SMB-C, < 0.25 mm-C	0.8651	0.288	68.4
	4.	WS-CHO, SMB-C, < 0.25 mm-C, WS-OC	0.8735	0.0084	53.5
	5.	WS-CHO, SMB-C, < 0.25 mm-C, WS-OC, 0.5-0.25 mm-C	0.8830	0.0095	45.3
Total N uptake	1.	Ws-CHO	0.6638	-	67.1
	2.	WS-CHO, WS-OC	0.7369	0.0731	46.2
	3.	WS-CHO, WS-OC, 0.5-0.25 mm-C	0.8015	0.0646	43.1
	4.	WS-CHO, WS-OC, 0.5-0.25 mm-C, 2-1 mm-C	0.8359	0.0344	39.5
	5.	WS-CHO, WS-OC, 0.5-0.25 mm-C, 2-1 mm-C, HA-C	0.8402	0.0043	31.5
Total P uptake	1.	WW-CHO	0.7617	-	108.7
	2.	WS-CHO, SMB-C	0.7759	0.0142	57.1
	3.	WS-CHO, SMB-C, 1-0.5 mm-C	0.7818	0.0059	38.2
	4.	WS-CHO, SMB-C, 1-0.5 mm-C, 2-1 mm-C	0.7913	0.0095	29.4
	5.	WS-CHO, SMB-C, 1-0.5 mm-C, 2-1 mm-C, 0.5-0.25 mm-C	0.7969	0.0056	23.5
Total S uptake	1.	WS-CHO	7619	-	108.8
	2.	WS-CHO, SMB-C	0.7857	0.0238	60.5
	3.	WS-CHO, SMB-C, 0.5-0.25 mm-C	0.8070	0.0213	44.6
	4.	WS-CHO, SMB-C, 0.5-0.25 mm-C, HA-C	0.8295	0.0225	37.7
	5.	WS-CHO, SMB-C, 0.5-0.25 mm-C, HA-C, FA-C	0.8507	0.0212	34.2

Table 4.44 Coefficient of correlation 'r' between nutrient pools, wheat grain yield and nutrient's supply

SOM pools	Grain yield	Nutrient's supply		
		N	P	S
Active pools				
Available N	0.86161	0.82587	0.80909	0.84138
SMB-N	0.82307	0.76382	0.81971	0.81467
WS-N	0.77816	0.72060	0.76433	0.798820
Available P	0.82947	0.78505	0.85944	0.83095
SMB-P	0.89585	0.78666	0.78012	0.83124
WS-P	0.87920	0.83100	0.78965	0.87552
Available S	0.87749	0.81282	0.81826	0.85735
SMB-S	0.88150	0.83802	0.80318	0.85459
WS-S	0.75936	0.70670	0.70201	0.75692
Passive pools				
HA-N	0.79416	0.75146	0.79956	0.83177
FA-N	0.81173	0.73826	0.78937	0.80183
HA-S	0.86107	0.80883	0.79751	0.85531
FA-S	0.877949	0.81137	0.82303	0.82876

All the values are significant at 1% level of significance

To study the relative contributions of different nutrient pools to wheat productivity as well as N, P and S uptake, the linear stepwise regression equations were computed and presented in Table 4.45. A perusal of the data in this Table indicates that SMB-P, available-N, available-P and SMB-S were the most important nutrient pools contributing to the total variations in wheat grain yield and N, P and S uptake, respectively. The total variations explained individually by these nutrient pools were about 80, 70, 74 and 77 per cent in grain yield and N, P and S uptake, respectively. The second most important nutrient pool was available-N, SMB-N, available-N and available-S in case of grain yield and uptake of N, P and S, respectively.

4.7 Inter-Relationship among SOM Pools

Efforts has also been made to find out the inter-relationship among different SOM pools by computing simple coefficient of correlations 'r' as well as linear stepwise regression equations. The data with respect to coefficient of correlations 'r' are given in Table 4.46. A reference to this Table reveals that there was strong association among active Vs slow, passive Vs slow and active Vs passive pools of SOM as the values of 'r' among all these SOM pools were found significant and positive. However, WS-CHO gave the highest significant and positive correlation with C associated with 2-1 mm (0.800) and < 0.25 mm (0.743) size particles followed by WS-OC. The highest coefficient of correlation between passive pools of SOM (HA-C, FA-C) was found with C associated with > 2 mm soil fraction followed by C associated with 1-0.5 mm fraction. As far as association between active and passive pool was concerned, it was found that

Table 4.45 Step-wise regression data for the relationship between wheat grain yield, nutrient supply, Y, and nutrient pools

Dependent variable (Y)	Step No.	Variable on which Y is regressed	R^2	ΔR^2	F value
Grain yield	1.	SMB-P	0.8025	-	138.2
	2.	SMB-P, AV-N	0.8352	0.0327	83.6
	3.	SMB-P, AV-N, WS-N	0.8856	0.0504	82.6
	4.	SMB-P, AV-N, WS-N, SMB-N	0.8983	0.0127	68.5
	5.	SMB-P, AV-N, WS-N, SMB-N, AV-P	0.9135	0.0152	63.3
	6.	SMB-P, AV-N, WS-N, SMB-N, AV-P, WS-P	0.9242	0.0107	58.9
	7.	SMB-P, AV-N, WS-N, SMB-N, AV-P, WS-P, AV-S	0.9309	0.0067	53.9
	8.	SMB-P, AV-N, WS-N, SMB-N, AV-P, WS-P, AV-S, SMB-S	0.9330	0.0021	67.3
Total N uptake	1.	AV-N	0.7023	-	80.2
	2.	AV-N, SMB-N	0.7218	0.0195	42.8
	3.	AV-N, SMB-N, AV-P	0.7345	0.0127	29.5
	4.	AV-N, SMB-N, AV-P, SMB-S	0.7519	0.0174	23.5
	5.	AV-N, SMB-N, AV-P, SMB-S, AV-S	0.7039	0.0120	19.4
	6.	AV-N, SMB-N, AV-P, SMB-S, AV-S, WS-N	0.7780	0.0141	16.9
	7.	AV-N, SMB-N, AV-P, SMB-S, AV-S, WS-N, HA-S	0.7861	0.0081	14.7
Total P uptake	1.	AV-P	0.7386	-	96.1
	2.	AV-P, AV-N	0.7581	0.0195	51.7
	3.	AV-P, AV-N, AV-S	0.8218	0.0637	49.2
	4.	AV-P, AV-N, AV-S, SMB-P	0.8418	0.0200	41.2
	5.	AV-P, AV-N, AV-S, SMB-P, SMB-N	0.8887	0.0469	47.9
	6.	AV-P, AV-N, AV-S, SMB-P, SMB-N, SMB-S	0.9061	0.0174	46.6
	7.	AV-P, AV-N, AV-S, SMB-P, SMB-N, SMB-S, WS-P	0.9084	0.0023	47.9
	8.	AV-P, AV-N, AV-S, SMB-P, SMB-N, SMB-S, WS-P, WS-S	0.9133	0.0049	42.1
Toatl S uptake	1.	SMB-S	0.7665	-	111.6
	2.	SMB-S, AV-S	0.7765	0.01	57.31
	3.	SMB-S, AV-S, SMB-P	0.7876	0.111	39.5
	4.	SMB-S, AV-S, SMB-P, AV-P	0.8008	0.0132	31.2
	5.	SMB-S, AV-S, SMB-P, AV-P, SMB-N	0.8151	0.0143	26.5
	6.	SMB-S, AV-S, SMB-P, AV-P, SMB-N, AV-N	0.8204	0.0053	22.1

Table 4.46 Coefficient of correlation 'r' among different SOM pools

SOM pools	Slow pools				
	> 2mm	2-1 mm	1-0.5 mm	0.5-0.25 mm	< 0.25 mm
Active pools					
WS-OC	0.75359	0.96282	0.56018	0.53909	0.80790
WS-CHO	0.64797	0.79988	0.46366	0.60402	0.74329
SMB-C	0.63028	0.79619	0.42031	0.39996	0.72367
Passive pools					
HA-C	0.51764	0.32341	0.46677	0.37475	0.43778
FA-C	0.50178	0.28942	0.44222	0.34805	0.43370

	Passive pools	
Active pools	HA-C	FA-C
WS-OC	0.66648	0.67184
WS-CHO	0.76716	0.77314
SMB-C	0.44856	0.44891

WS-CHO was the most important active pool of SOM contributing to the passive pools of SOM, as it had the highest coefficient of correlations 'r' both with HA and FA-C. This was followed in turn by WS-OC.

To study the relative contribution of every active SOM pool to every slow pool, every passive pool to every slow pool and every active pool to every passive pool, linear stepwise regression equations were also computed and

given in Table 4.47. It is interesting to note that WS-OC was found to be the most important active pool of SOM on which major variations in SOM associated with different soil size fractions (> 2 mm to < 0.25 mm) could be explained. The second most important active SOM pool on which SOM associated with different soil size fraction was WS-CHO. The total variations explained by WS-OC and WS-CHO together were about 62, 21, 36, 39 and 66 per cent in SOM associated with > 2 mm, 2-1 mm, 1-0.5 mm, 0.5-0.25 mm and < 0.25 mm, respectively.

When the relative contribution of SOM associated with different soil size fractions to passive pools of SOM was studied, it was found that SOM pool associated with > 2 mm soil size fraction was the most important slow pool of SOM contributing towards passive pools of SOM (HA-C and FA-C). The SOM pool associated with 2-1 mm soil size fraction was the second most important fraction for explaining total variations in slow pools of SOM.

The relative contribution of different active pools of carbon towards passive pools was also studied. Water soluble-CHO was found to be the most active pool contributing to the total variations in passive pool of carbon (HA-C and FA-C). The total variations explained by this active pool was about 59 and 60 per cent in HA-C and FA-C, respectively. The second most important active pool contributing to the total variations of passive pools was SMB-C. The values of ΔR^2 indicate that the total variations explained only by SMB-C was about 10 per cent in HA-C as well as FA-C.

Table 4.47 Step-wise regression data for the relationship between SOM pools

Dependent variable (Y)	Step No.	Variable on which Y is regressed	R^2	ΔR^2	F value
> 2 mm	1.	WS-OC	0.5679	-	44.7
	2.	WS-OC, WS-CHO	0.6238	0.0559	27.4
	3.	WS-OC, WS-CHO, SMB-C	0.6604	0.0925	20.7
2-1 mm	1.	WS-OC	0.0385	-	1.36
	2.	WS-OC, WS-CHO	0.2154	0.1769	4.53
	3.	WS-OC, WS-CHO, SMB-C	0.3441	0.1287	5.59
1-0.5 mm	1.	WS-OC	0.3138	-	15.5
	2.	WS-OC, WS-CHO	0.3694	0.0556	9.67
	3.	WS-OC, WS-CHO, SMB-C	0.4464	0.077	8.60
0.5-0.25 mm	1.	WS-OC	0.3648	-	19.5
	2.	WS-OC, WS-CHO	0.3926	0.0278	10.7
< 0.25 mm	1.	WS-OC	0.6527	-	63.9
	2.	WS-OC, WS-CHO	0.66111	0.0084	32.2
HA-C	1.	> 2 mm-C	0.2680	-	12.4
	2.	> 2 mm-C, 2-1 mm-C	0.3415	0.0735	8.5
	3.	> 2 mm-C, 2-1 mm-C, 1-0.5 mm-C	0.3860	0.0445	6.7
FA-C	1.	> 2 mm-C	0.2518	-	11.4
	2.	> 2 mm-C, 2-1 mm-C	0.3088	0.057	7.3
	3.	> 2 mm-C, 2-1 mm-C, 1-0.5 mm-C	0.3619	0.0531	6.0
HA-C	1.	WS-CHO	0.5885	-	48.6
	2.	WS-CHO, SMB-C	0.6880	0.0995	36.4
FA-C	1.	WS-CHO	0.5977	-	50.5
	2.	WS-CHO, SMB-C	0.7023	1.046	38.9

4.8 Validation of Carbon Models

4.8.1 Roth-C Model

As part of model evaluation exercise Roth-C 26.3 model for the build-up of SOC in arable soils was fitted to measurements of OC values for 17 years in a long-term field experiments initiated in 1988. The fits between observed and simulated data for twelve treatment combinations of four levels of lantana addition and three levels of fertilizer in long-term field experiments are depicted into Figures 4.2 to 4.5.

In the modeling exercise, the objective was to check the use of Roth-C model with its internal structure and internal parameters unaltered, to give a plausible fit to the experimental data, altering only the annual input of plant debris to the soil assuming that there was always 1.194 t C ha^{-1} of biologically inert organic carbon (IOM) in the surface soil layer. Initial carbon value was 16.5 t ha^{-1} with 1.194 t C ha^{-1} contribution from IOM which makes a large difference to the predicted SOC. Starting from 1988 SOC values, the Roth-C model predicted the observed values reasonably correct upto 2004, since the values predicted by the model past nearly through measured values in all the twelve treatments.

Under no lantana addition along with different levels of fertilizer application (33 to 100 per cent), the observed increase in SOC was closely related with simulated SOC from 1988 to 2004 with variations in RMSE from 0.30 to 0.74 (Fig. 4.2). Similarly, when measured SOC values were compared to simulated SOC data for the addition of 10 t ha^{-1} lantana, the RMSE values of 2.76, 3.08 and 3.23 under 33, 66 and 100 per cent of RD respectively, indicated

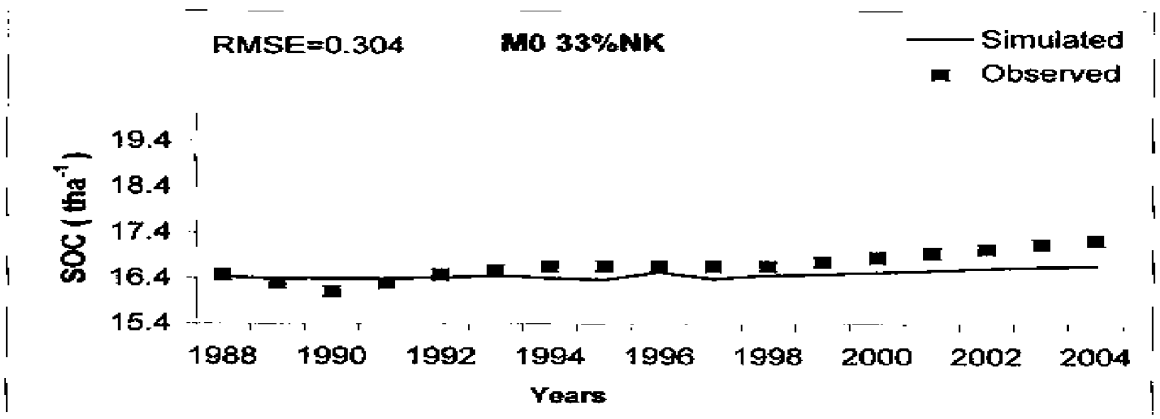


Fig. 4.2a

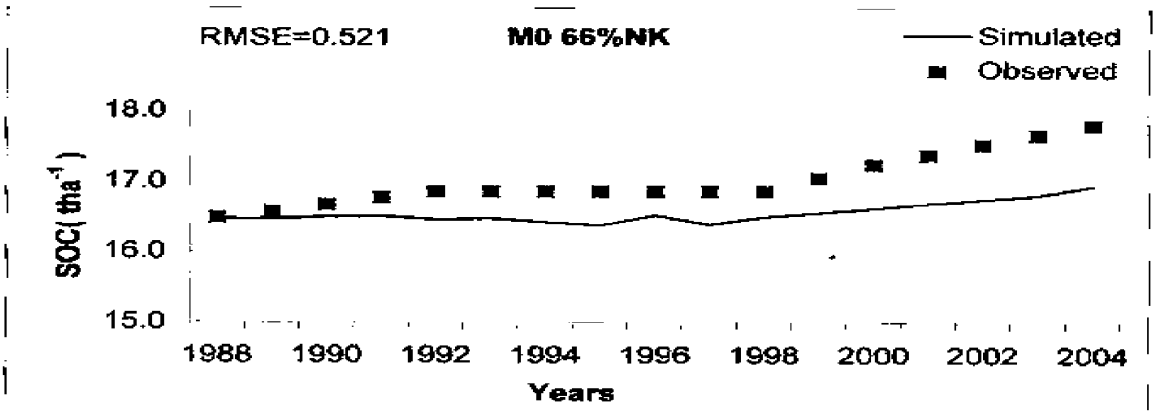


Fig. 4.2b

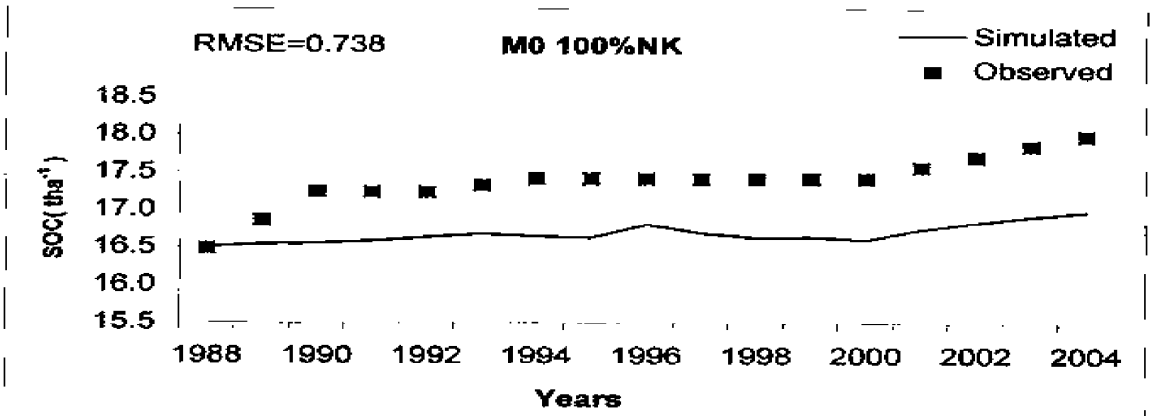


Fig. 4.2c

Fig. 4.2 Simulated and observed organic carbon content (t C ha^{-1}) predicted by Roth-C model under no lantana addition (4.2a, M_0 33% NK), (4.2b, M_0 66% NK), (4.2c, M_0 100% NPK)

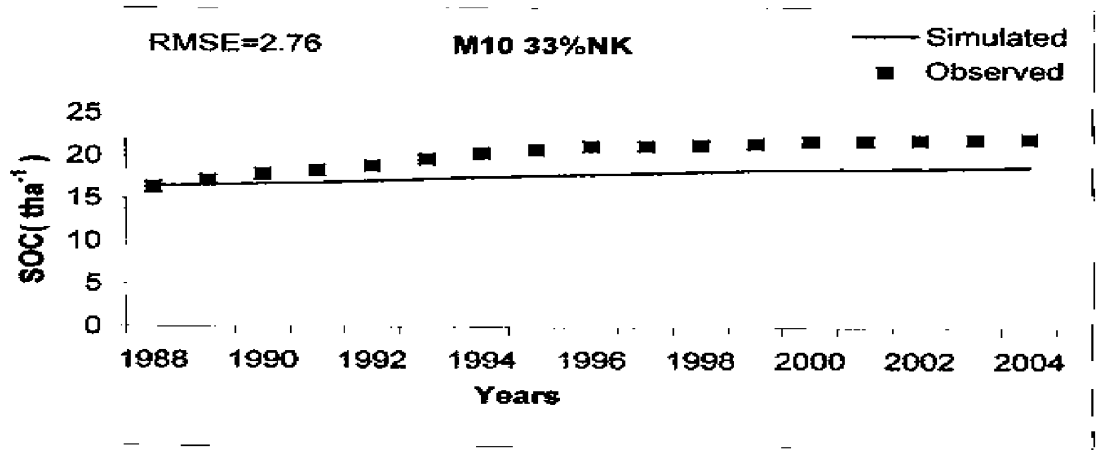


Fig. 4.3a

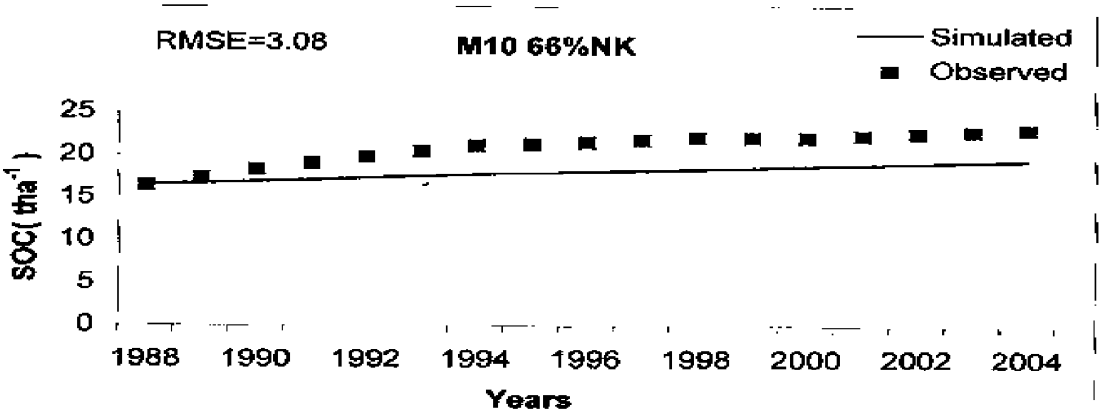


Fig. 4.3b

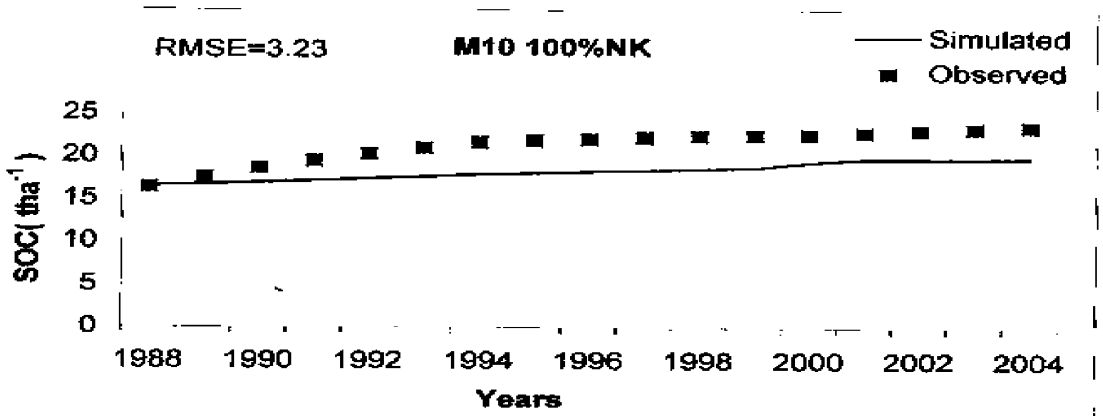


Fig. 4.3c

Fig. 4.3 Simulated and observed organic carbon content (t C ha^{-1}) predicted by Roth-C model under 10 t ha^{-1} lantana addition (4.3a, M_{10} 33% NK), (4.3b, M_{10} 66% NK), (4.3c, M_{10} 100% NPK)

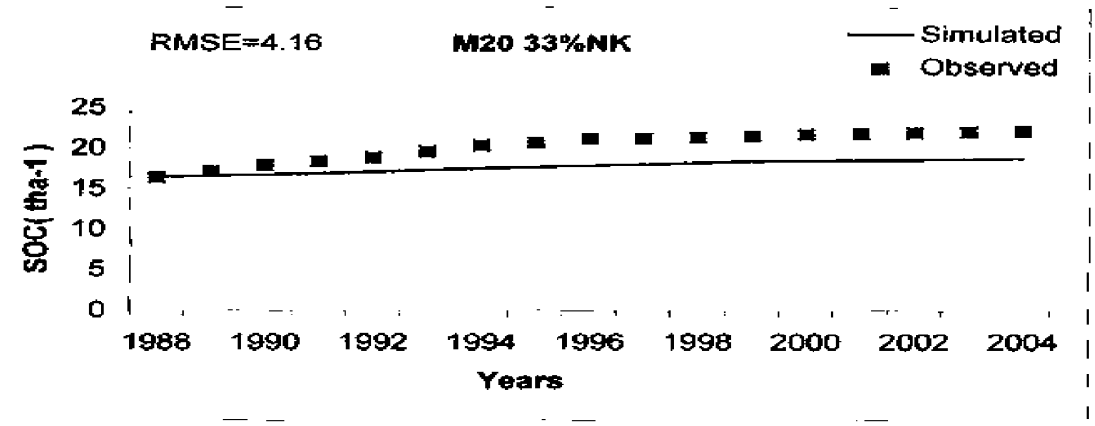


Fig. 4.4a

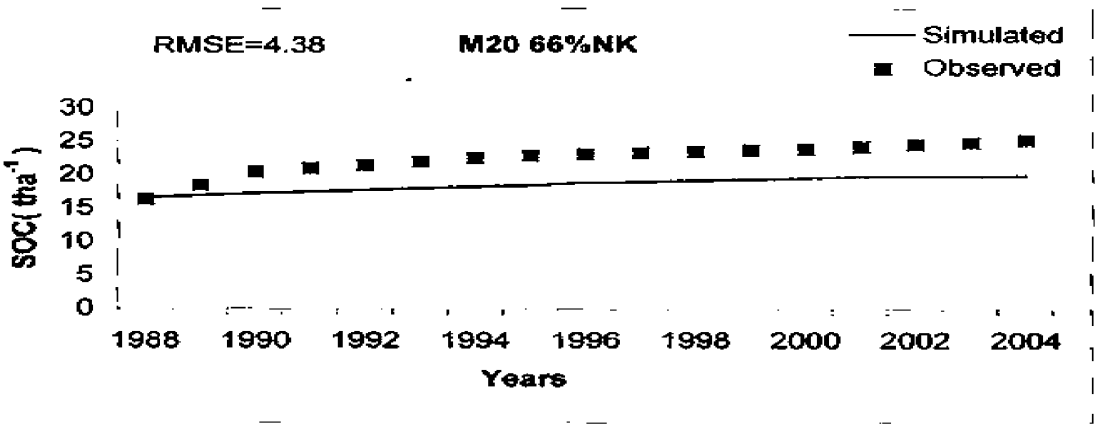


Fig. 4.4b

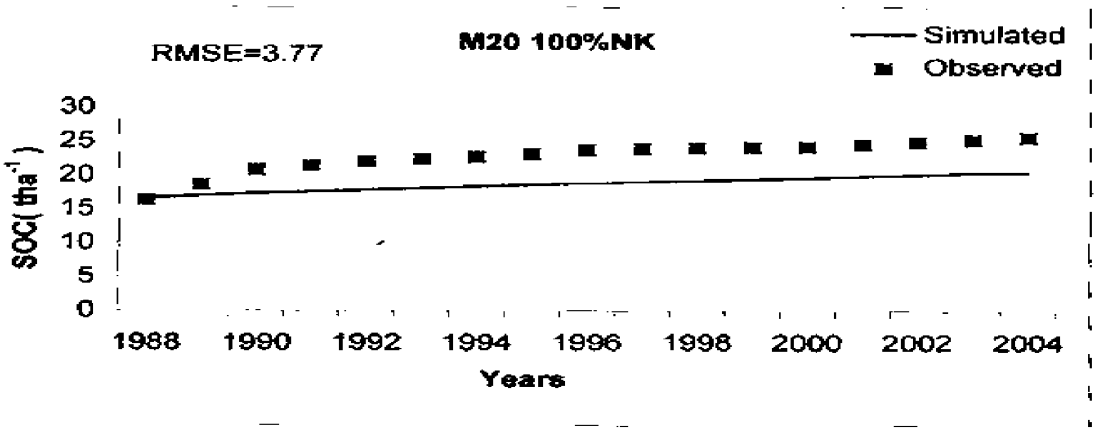


Fig. 4.4c

Fig. 4.4 Simulated and observed organic carbon content (t C ha^{-1}) predicted by Roth-C model under 20 t ha^{-1} lantana addition (4.4a, M_{20} 33% NK), (4.4b, M_{20} 66% NK), (4.4c, M_{20} 100% NPK)

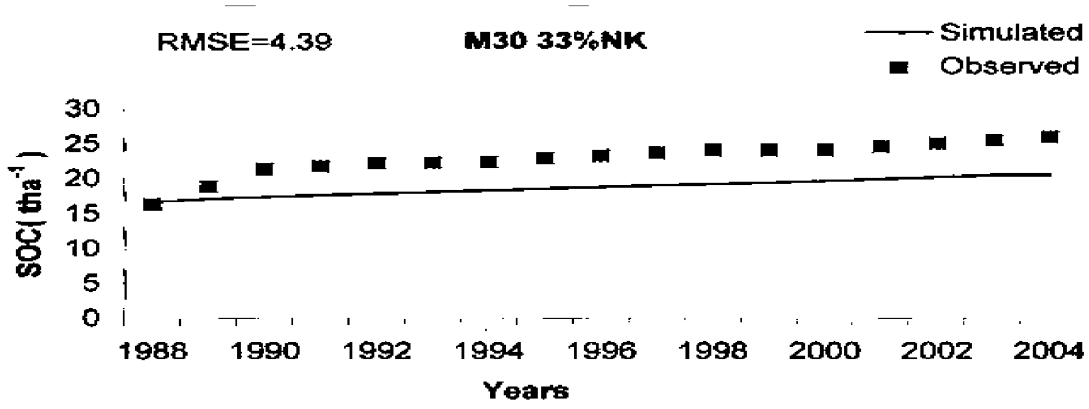


Fig. 4.5a

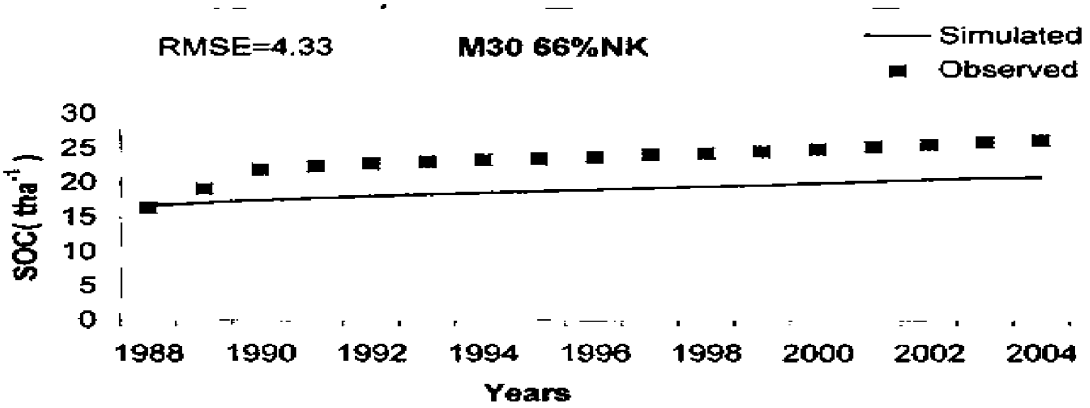


Fig. 4.5b

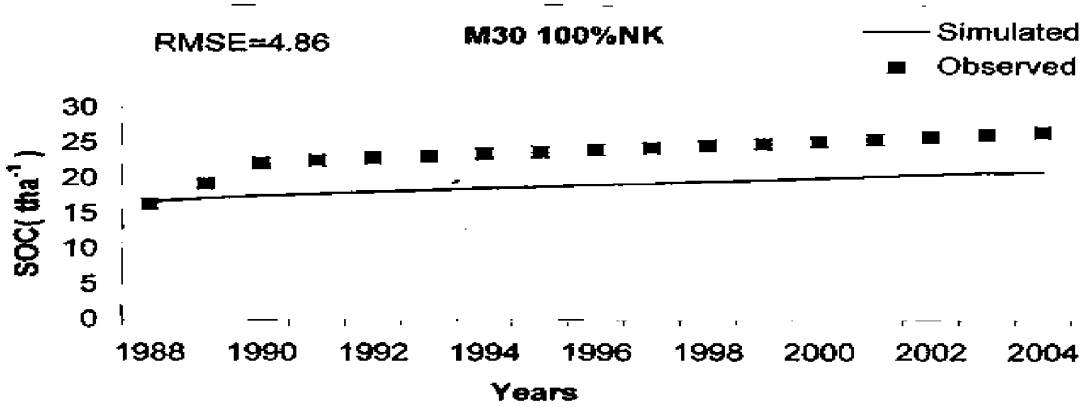


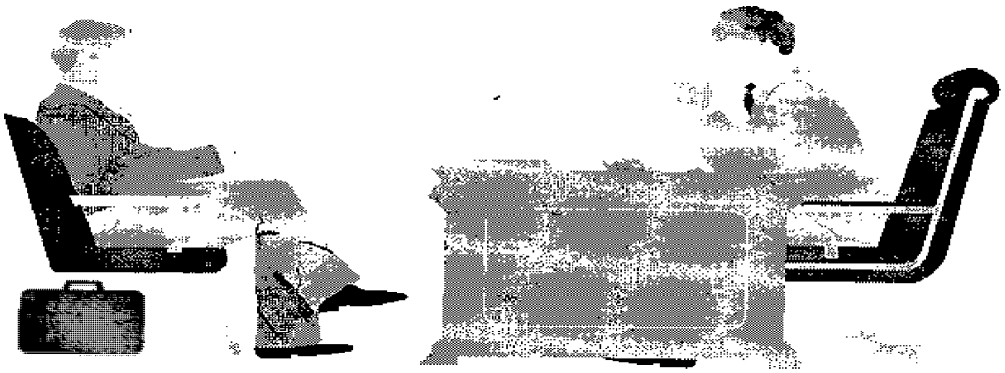
Fig. 4.5c

Fig. 4.5 Simulated and observed organic carbon content (t C ha^{-1}) predicted by Roth-C model under 30 t ha^{-1} lantana addition (4.5a, M_{30} 33% NK), (4.5b, M_{30} 66% NK), (4.5c, M_{30} 100% NPK)

a good approximation of the data over the period 1988-2004 (Fig. 4.3). Almost a good fit between observed SOC with simulated one was also observed under 20 to 30 t ha^{-1} lantana addition with different fertilizer levels. Somewhat higher values of RMSE under 20 and 30 t ha^{-1} lantana addition in comparison to zero and 10 t ha^{-1} lantana addition, indicated that as the C stock increased in the soil, the variations between observed and simulated SOC also increased. However, looking into the close association between observed and simulated values in the build up of SOC stock in the soil in twelve treatment combinations of four levels of lantana and three levels of fertilizer application over the last 17 years (Fig. 4.4 to 4.5), it was observed that Roth-C-26.3 model could very well be used for predicting build up in SOC stock even under temperate climatic conditions.

4.8.2 Carbon and Nitrogen Dynamics (CANDY) Model

The carbon and nitrogen dynamics (CANDY) model could not be used in the present study for the want of required data input.



Discussion

Chapter V

DISCUSSION

The experimental results obtained in the present study were given in the previous chapter and have been discussed in the present section in light of relevant literature. The effect of long term lantana addition and fertilizer application is discussed under the following sub-heads:

5.1 Carbon Sequestration and SOM dynamics

5.2 Carbon Pools

5.3 Pools of N, P and S in Soils

5.4 Chemical Environment of Soils

5.5 Microbial Environment of soils

5.6 Physical Environment of soils

5.7 Rice and wheat Productivity

5.8 Nutrient Uptake

5.9 Relationship between SOM Pools, Crop Productivity and Nutrient's Supply

5.10 Inter-relationships between Carbon-Pools

5.11 Validation of Carbon-Models

5.1 Carbon sequestration and SOM dynamics

The periodic changes in C stock was worked out over the last 17 years (1988-2004) with an interval of two years on original soil mass basis at 1.25 Mgm^{-3} BD. Irrespective of fertilizer application, increasing levels of lantana from

10 to 30 t ha^{-1} increased C stocks with advancement of time (Table 4.29). Similarly, increasing levels of fertilizers from 33 to 100 per cent of RD also resulted in an increase in C-stock over the years but increase was quite less when compared with lantana addition. Since lantana addition and fertilizer application individually increased C-stock over the years, they also had additive effect on C-stock build-up. The minimum C stock build was observed under no lantana addition along with 33 per cent of RD and maximum under 30 t ha^{-1} lantana addition along with 100 per cent RD. The present experiment was in progress since 1988 and lantana at the rate of 10 to 30 t ha^{-1} was continuously added every year before the transplanting of rice. On an average, lantana spp. contained 52.5 per cent C. The addition of such high amount of C through lantana addition every year has resulted in continuous build-up in C stock in the present study. In literature the addition of plant residues have also been reported to increase SOC (Rasmussen and Collins, 1991; Verma and Bhagat, 1992).

An attempt has also been made to calculate the build-up in C-stock ha^{-1} yr^{-1} basis. Like C stock build-up over the years, it was found that lantana addition at the rate of 10, 20 and 30 t ha^{-1} also increased C stocks ha^{-1} yr^{-1} basis by 0.25, 0.35 and 0.41 Mg when compared with no lantana addition. Similarly, increasing levels of fertilizer application also resulted in an increase in C stock ha^{-1} yr^{-1}. This clearly indicates that more the addition of C through lantana more was the build-up in C-stock ha^{-1} yr^{-1} in the present study.

In the present study the total C added over 17 years at 10, 20 and 30 t ha^{-1} on fresh weight basis (OC 52.5 per cent) corresponded to 32.13, 64.26 and 96.39 t OC ha^{-1} in 0-0.30 m soil depth. The OC retained in soil after 17 years of

experimentation on soil mass basis was found to be 5.21, 6.14 and 7.54 t ha^{-1} at 10, 20 and 30 t ha^{-1} lantana addition. The total SOM was also determined by dry combustion method. It was found that SOM retained in 0-0.30 m soil depth was 8.99, 10.64 and 13.00 t ha^{-1} at 10, 20 and 30 t ha^{-1} lantana addition when compared with no lantana addition. These values of SOM retention corresponded to 27.98, 15.00 and 12.45 per cent of the total C added through lantana over the last 17 years. In most of the studies it has been reported that depending upon climatic conditions and soil type, about 60-75 per cent of the added C was lossed to the atmosphere in the form of CO_2. This loss was always higher under tropical conditions and somewhat less under temperate condition (Christensen, 1986; Ramussen and Collins, 1991; Brar and Dhillon, 1994). These studies concluded that in order to initiate OC build-up in soil, OC must exceed 2.5 t ha^{-1} yr^{-1}. This quantity correspond to about 5 t ha^{-1} of lantana dry matter which was equivalent to about 15 t ha^{-1} on fresh weight basis.

Efforts have also been made to study the distribution of SOM retained in soil into different active and passive pools in 0-0.30 m soil depth. It was observed that on an average the major portion of retained SOM was found in passive pools (60.43 per cent) and only small fraction was in active pools (10.63 per cent). These two fractions of C in soil accounted about 71 per cent of total retained OM in soils. This clearly indicates that about $1/4^{th}$ of added OM must have also been transformed to humin fractions. It is noteworthy to indicate here that, the increasing levels of lantana increased the retention of C in active pools and decreased it in passive pools. The higher retention of added OM in active

pools with increasing levels of lantana might have resulted in decrease in passive pools. Out of total C retained in active pools the maximum portion was found to be retained in WS-CHO followed by SMB-C and minimum in WS-OC with average values of 4.80, 3.59 and 2.24 per cent, respectively. The highest retention of C in WS-CHO could be because of increase in bacterial population (Table 4.20) resulting in higher content of bacterial polysaccharides, which comprise WS-CHO. The high WS-CHO also causes aggregation of soil structure and build-up in SOM (Martin, 1945 and Kononova, 1975).

The lantana addition from 10 to 30 t ha^{-1} increased the C retention in all the active pools (WS-OC, WS-CHO, SMB-C). Among passive pools (HA-C and FA-C), the higher retention was observed in FA-C (31.59 per cent) than in HA-C (28.83 per cent). The higher FA-C content in the present study might be ascribed due to the podzolic nature of soil having acidic environment (Kononova, 1975). Like total passive pools, the retention in C retained by HA-C and FA-C was also decreased with increasing lantana addition.

The distribution of total SOM retained in 0-0.30 m soil depth was further studied in surface (0-0.15 m) and subsurface (0.15-0.30 m) soil depths (Table 4.31). Out of 18.48 per cent of the total C added through lantana in 0-0.30 m soil depth, 15.7 per cent was found to be retained in surface soil depth and only 3.7 per cent in subsurface soil depth.

Similarly, the C retained in active and passive pools as a fraction of total SOM retained in two soil depths together was also studied. Like 0-0.30 m soil depth, the higher amount of C was found to be retained in passive pools when compared with C in active pools in both the soil depths. On an average, the

reduction in subsurface soil depth was 55 per cent in passive pools and about 24 per cent in active pools indicating more accumulation of passive pools C in surface depth in comparison to subsurface depth. All the active (WS-OC, WS-CHO, SMB-C) and passive (HA-C and FA-C) pools of C were also found to be higher in surface depth in comparison to subsurface soil depth. The average reduction in WS-OC, WS-CHO, SMB-C, HA-C and FA-C was about 33, 18, 29, 55 and 55 per cent in subsurface soil depth. Like 0-0.30 m soil depth, continuous lantana addition from 10 to 30 t ha^{-1} resulted in an increase in all the active pools and decrease in passive pools in both the soil depths. The higher retention of C either in active or in passive pools in surface soil depth in comparison to subsurface soil depth might be because of the fact that every year lantana was added and mixed thoroughly only in surface soil depth. What so ever build-up was observed in these pools of C in subsurface soil depth might be because of downward movement of C due to climatic and crop management factors over the years under rice-wheat cropping system.

5.2 Carbon Pools

Soil organic carbon is considered to be one of the most important pools of SOM. Its amount and nature plays a key role in soil quality (Larson and Pierce, 1992). Organic carbon although is not a plant nutrient, its low amount can have deleterious effect on soil health and crop productivity (Stevenson, 1982). Therefore, maintenance or improvement in the OC content of the soil is of utmost importance. In the present study, OC content in both the soil depths did not show any significant variations with the application of fertilizers. Conversely, lantana

addition resulted in significant and consistent build-up in OC in comparison to control (Table 4.3). In general, the increase in OC content amounted to about 30, 43 and 49 per cent in surface layer and 12, 19 and 28 per cent in subsurface soil depth under 10, 20 and 30 t ha^{-1} lantana addition, respectively. Irrespective of lantana addition and fertilizer application, OC was 12.3 g kg^{-1} in surface depth and 8.6 g kg^{-1} in subsurface depth, indicating a decrease of about 30 per cent in subsurface layer in comparison to surface layer. The build-up in OC content in the present study was mainly due to continuous addition of lantana since 1988 as it contained on an average 52.5 per cent C (Verma and Bhagat, 1992).

Active pools

The active pools of C (WS-OC, WS-CHO and SMB-C) are considered as the most labile, mobile and readily available source of energy for micro-organisms and contribute to soil quality through their role in the formation and stabilization of soil structure (Mc Gill *et al.*, 1981). In general, the range of variations in WS-OC, WS-CHO and SMB-C was found to be 40-168, 495-816 and 292-520 mg kg^{-1} in surface soil depth and 28-117, 394-641 and 190-340 mg kg^{-1} in subsurface soil depth, respectively (Table 4.4 to 4.6). In general, WS-CHO was the highest.

Irrespective of lantana addition and fertilizer application, the average content of WS-OC, WS-CHO and SMB-C was about 101, 640 and 390 mg kg^{-1} in surface layer and 70, 25 and 263 mg kg^{-1} in subsurface layer. The average reduction was found to be 31, 18 and 33 per cent in subsurface layer in comparison to surface layer in WS-OC, WS-CHO and SMB-C, respectively.

Since lantana additions were made continuously from 1988 to 2004 only in surface layer, the higher content of WS-OC, WS-CHO and SMB-C in surface layer was quite understandable in present study.

Irrespective of fertilizer application, lantana addition from 10 to 30 t ha^{-1} increased all the three active pools of C significantly and consistently. Similarly, fertilizer application from 33 to 100 per cent of RD also resulted in significant build-up in active pools of C in soil. In general, the per cent increase under 10, 20 and 30 t ha^{-1} lantana addition in surface soil depth was observed to be 67, 127 and 196 in WS-OC; 9, 27 and 36 in WS-CHO; and 14, 31 and 57 in SMB-C, respectively. The corresponding increase in subsurface soil depth was 70, 141 and 206 in WS-OC; 9, 27 and 36 in WS-CHO; and 20, 37 and 56 in SMB-C. The interaction between lantana addition and fertilizer application was found significant on WS-CHO in surface depth.

It was observed that lantana addition from 10 to 30 t ha^{-1} increased WS-OC and SMB-C under all the levels of fertilizer application. However, fertilizer application while increased WS-OC significantly in the presence of lantana addition, did not influenced its content in the absence of lantana addition. In contrast to this fertilizer application under all the levels of lantana addition and lantana addition under all the levels of fertilizer application increased SMB-C significantly. Addition of fresh organic material to the soil in the form of continuous lantana addition over the last 17 years might have stimulated the microbial activity and mineralization of N which might have resulted in decomposition of SOM with rapid release of active pools of carbon (Collins *et al.*,

1992; Ritz *et al.*, 1997; and Yagi *et al.*, 2005). The lowest content of WS-OC, WS-CHO and SMB-C in the present study was observed under no lantana addition along with 33 per cent of RD and highest with 30 t ha^{-1} lantana addition along with 100 per cent of RD. This indicates that there was an additive effect of lantana addition and fertilizer application on the build up of active pools of C in the soil.

Slow pools

Soil aggregation is considered to be one of the important processes of stabilizing OM pools, therefore, characterization of WSAC, also known as slow pool of SOM, is important in maintenance of soil fertility. Soil organic matter is the major binding agent and aggregation is hierarchical in which primary particles and clay domains are cemented into micro-aggregates and later into macro aggregates. A reference to Table 4.7 and Fig. 4.1 indicates that WSAC, in general, was higher in 2-1 mm soil size fraction followed by > 2 mm and 1-0.5 mm in both the soil depths. Like total SOC in the soil, WSAC was also high in all the soil size fraction in surface soil as compared to subsurface soil depth. These results indicate that upon destruction of soil aggregates, much of the SOC is redistributed in finer soil fraction associated primarily with silt and clay fractions over the time. The finer fractions of soil aggregates provide protection for the SOM against microbial and enzymatic degradation. These results are in conformity with the results of earlier workers (Leinweber and Rutter, 1992; Singh and Singh, 1996).

In general, the C concentration in different soil size fractions increased with an increase in lantana addition from 10 to 20 t ha^{-1} whereas, a small decrease was noticed with 30 t ha^{-1} lantana addition in 0-0.15 m soil depth. This might be attributed to the build-up of SOC due to addition of lantana since last 17 years. It is interesting to note that if WSAC in two soil size fractions (1-0.5 and 0.5-0.25 mm) was grouped together, it was found that more than 50 per cent C was retained in these two soil size fractions in both the soil depths.

Passive pools

Passive pools comprises the fraction of SOM, which is most resistant to mineralization and decomposition. However, HA-C and FA-C are the important fraction of SOM whose build-up in soils help in nutrient restoration and transformation for higher crop productivity. In general, the application of chemical fertilizer either alone or in combination with organic additions over the years has resulted into significant build-up in humic and fulvic acid carbon content of the soil. A reference to Table 4.8 and 4.9 reveals that general variations in HA-C content in the present study was from 0.10-0.44 per cent in surface soil depth and from 0.10-0.28 per cent in sub-surface soil depth with average values of 0.28 and 0.19 per cent in surface and subsurface soil depths, respectively. Similarly, the FA-C content varied from 0.14-0.44 per cent in surface depth and 0.11-0.29 per cent in subsurface soil depth with average values of 0.29 per cent in surface and 0.20 per cent in subsurface soil depth. The FA-C was slightly higher when compared with HA-C which might be because of acidic environment of soils (Kononova, 1996 and Wang and Zhang, 1998). The average decrease in subsurface soil depth with respect to HA-C and FA-C was about 32 per cent. The

average contribution of HA-C towards SOC was 16 and 21 per cent in surface and subsurface soil depths, respectively. The corresponding values of FA-C towards SOC were 24 and 23 per cent in upper and lower soil depths, respectively. This indicates comparatively higher contribution of FA-C towards SOC in comparison to HA-C.

Individually, the increasing levels of lantana addition and fertilizer application increased HA-C and FA-C significantly and consistently in both the soil depths. Similarly, the contribution of these two passive pools of C towards SOC was also increased with an increase in lantana addition as well as fertilizer application. The higher content of HA-C and FA-C under increasing levels of lantana addition and fertilizer application is understandable because lantana is being added to soil continuously over the last 17 years which, in turn, might have helped in the build-up of passive pools of carbon as was a case with active pools of carbon. The minimum content of both HA and FA-C was observed under no lantana addition along with 33 per cent of RD and maximum under 30 t ha^{-1} lantana addition along with 100 per cent of RD in both the soil depths.

5.3 Pools of N, P and S in soils

The active and passive pools of nutrients have been discussed in this section with respect to N, P and S, separately.

Nitrogen

Active pools

With respect to active pools, soil nitrogen has been fractionated into available-N, WS-N and SMB-N. The average available-N varied from 327.6 kg ha^{-1} under 33 per cent of RD without lantana addition to 447.2 kg ha^{-1} under 100

per cent of RD along with 30 t ha^{-1} lantana addition with an average value of 391.4 kg ha^{-1} in surface soil depth (Table 4.10). The corresponding values in subsurface soil depth under above mentioned two treatments were 292.3, 388.2 and 332.8 kg ha^{-1}. This indicates about 15 per cent decrease in available-N content in subsurface layer in comparison to surface layer. The increasing levels of lantana addition and fertilizer application, increased available-N significantly and consistently in both the soil depths. Interaction between lantana addition and fertilizer application was found significant in both the soil depths. On an average, lantana addition from 10 to 30 t ha^{-1} increased available-N significantly under all the fertilizer levels, however, the application of fertilizer, increased available-N only when they were applied along with lantana addition in both the soil depths. This interaction was found in lines with increase in OC content with respect to lantana addition (Gattani *et al.,* 1976; Sharma, 1996).

In general, WS-N ranged from a minimum value of 13.53 mg kg^{-1} under no lantana addition along with 33 per cent of RD to a maximum value of 18.15 mg kg^{-1} under 30 t ha^{-1} lantana addition alongwith 100 per cent of RD (Table 4.11). The corresponding values in subsurface soil depth were from 8.5 to 14.40 mg kg^{-1}, respectively. The average contribution of WS-N towards available-N was about 9 per cent in surface depth and 8 per cent in subsurface depth. Similar to available-N, the increasing levels of lantana addition as well as fertilizer application also increased WS-N significantly and consistently in both the soil depths. The continuous addition of lantana as well as fertilizers since last 17 years has resulted into significant build-up in OC which, in turn, was responsible for increasing content of WS-N in the present study.

The content of SMB-N varied from a minimum value of 63.96 mg kg^{-1} under no lantana addition alongwith 33 per cent of RD to a maximum value of 90.93 mg kg^{-1} under 30 t ha^{-1} lantana addition along with 100 per cent of RD (Table 4.12). The corresponding values of SMB-N in subsurface soil depth were 24.76 and 40.76 mg kg^{-1}. There was about 56 per cent reduction in SMB-N in subsurface soil depth in comparison to surface soil depth. In general, the contribution of SMB-N towards available-N was about 43 per cent in surface depth and 22 per cent in subsurface depth. When the contribution of SMB-N and WS-N towards available-N was compared, it was found that SMB-N contributed about 5 times higher towards available-N in comparison to WS-N. This clearly indicates that amount of SMB-N in the present study was 5 times higher than WS-N. Individually, increasing levels of lantana addition as well as fertilizer application increased SMB-N significantly and consistently in both the soil depths. The interaction between lantana addition and fertilizer application on SMB-N was also found significant in both the soil depths. Lantana addition from 10 to 30 t ha^{-1} increased significantly and consistently SMB-N under all levels of fertilizer application in the surface soil depth but in subsurface soil depth lantana addition increased SMB-N significantly only over no lantana addition whereas, there was no significant difference among lantana levels (10 to 30 t ha^{-1}). The fertilizer application at 66 and 100 per cent of its RD did not influence SMB-N significantly without lantana addition in both the soil depths, however, with lantana addition (10 to 30 t ha^{-1}), these two levels of fertilizers increased SMB-N significantly and consistently. The increase in SMB-N with the addition of lantana and fertilizer application was understandable in the present study. Through the

addition of lantana there was significant build-up in different active, slow and passive pools of carbon. Out of these different C pools, the active pools are considered to be source of energy for microorganisms which, in turn, increased the SMB-N in the soil (Mc Gill *et al.,* 1986).

Passive pools

The average content of HA-N and FA-N was 1.10 and 0.35 per cent in surface depth and 0.71 and 0.26 per cent in subsurface soil depth, respectively (Table 4.19). This clearly indicates that HA-N was reduced in the subsurface soil in comparison to surface soil depth by about 36 per cent and FA-N by about 26 per cent. When these two fractions of N were compared among themselves, it was found that FA-N content was about 3 times less in surface depth and 2.75 times less in subsurface soil depth when compared with HA-N.

The fertilizer application in general, increased FA-N significantly and consistently in both the soil depths and HA-N only in surface soil depth. However, the addition of lantana from 10 to 30 t ha^{-1} over no lantana addition, increased both the passive fraction of N significantly and consistently in both the soil depths. This increase in passive pools of N under increasing levels of lantana might be because of more carbon added through this waste material over the years.

Phosphorus

Active pools

Like available-N, the minimum available-P content was observed under no lantana addition along with 33 per cent of RD and maximum under 30 t ha^{-1} lantana addition along with 100 per cent of RD in both the soil depths. On an

average, there was about 53 per cent higher available-P content in surface soil depth in comparison to subsurface soil depth (table 4.13). Irrespective of fertilizer application, lantana additions at the rate of 10, 20 and 30 t ha^{-1} over no lantana, increased available-P content significantly and consistently in both the soil depths. Similarly, increasing fertilizer application also increased available-P significantly and consistently in both the soil depths. The increase in available-P content under lantana addition as well as fertilizer application could mainly be because of additional P added either by way of lantana addition or by high turn over of root mass under increased level of fertilization (Ganai and Singh, 1998; Bhardwaj and Omanwar, 1994; Sharma, 1966). The build-up of available-P in the present study may also be attributed to the fact that, present soils contain fairly good amount of clay and silt (30.1 and 52.7 per cent) vis-à-vis crystalline and amorphous form of Al and Fe (Singh *et al.,* 1993) which are the potential sites for P fixation (Ballard and Fiskell, 1974) and consequently some quantity of P added through organic or inorganic sources could be transferred to Ca-P, Al-P and Fe-P due to such fixation in soils (Sharma, 1996). Such fractions serve as a source of available-P in soils, because Olsen's extractant has been reported to remove P from such fractions by many workers (Sharma and Tripathi, 1984; Paliyar, 1988). The increase in available-P in the presence of organic manures and crop residues may also be due to solvent action of organic acids produced in the soil after decomposition of organic materials (Singh and Subbiah, 1969).

The interaction between lantana addition and fertilizer application was found significant on available-P only in surface depth. Like available-N, the lantana addition from 10 to 30 t ha^{-1} over no lantana increased available-P under

all the levels of fertilizer application. However, fertilizer application increased available-P only under higher levels of lantana (20 to 30 t ha^{-1}) whereas, either under no lantana or 10 t ha^{-1} lantana addition, fertilizer application did not increased available-P significantly.

Water soluble-P, in general, varied from 1.23 to 5.00 mg kg^{-1} in surface and 0.70 to 2.77 mg kg^{-1} in subsurface soil depth (Table 4.14). The average content of WS-P in surface soil was 4.25 mg kg^{-1} which was reduced to 2.21 mg kg^{-1} in subsurface soil depth, indicating a decrease of about 50 per cent. Increasing levels of lantana addition and fertilizer application, individually, increased WS-P significantly and consistently in both the soil depths. The interaction between lantana addition and fertilizer application was also found significant in both the soil depths. Like available-P, lantana addition increased WS-P significantly under all the levels of fertilizer application, however, fertilizer application at the rate of 66 and 100 of its RD increased WS-P only in the presence of lantana addition. On an average, WS-P constituted about 45 per cent of available-P in surface depth and about 50 per cent in subsurface soil depth. The soils under present study are acidic in nature and continuous addition of lantana over the last 17 years has resulted in an increase in soil pH (Table 4.23). In acidic soils most of the P is fixed by forming Fe and Al complexes and increase in soil pH reduce the activity of Fe and Al and thus increased the available-P as well as water extractable P content (Mckenzie *et al.*, 1992).

The SMB-P ranged from a minimum value of 0.44 mg kg^{-1} under no lantana addition along with 33 per cent of RD to a maximum value of 2.59 mg kg^{-1} under 30 t ha^{-1} lantana addition alongwith 100 per cent of RD in the surface

depth. The corresponding values of SMB-P in subsurface soil for these two treatments were 0.30 and 1.35 mg kg^{-1}, respectively. The average SMB-P was 1.38 mg kg^{-1} in surface layer and 0.88 mg kg^{-1} in subsurface layer indicating a decrease of about 36 per cent. In contrast to WS-P, SMB-P constituted about 15 per cent of available-P in surface depth and 20 per cent in subsurface soil depth. In general, SMB-P was about 3.1 and 2.5 times less in surface and subsurface soil depths when compared with WS-P in these two soil depths. The comparatively low content of SMB-P to available P might be because of the fact that in soils the majority of P is always present in inorganic form and very little amount is in organic form.

Both, the addition of lantana and fertilizer application, increased SMB-P significantly and consistently in both the soil depths. In the present study lantana is being added continuously at different levels since last 17 years. With advancement of time, the previously added lantana might have decomposed thus provided substrates essential for microbial growth resulting in an increase in activity and hence increased microbial count (Table 4.20 to 4.22). This increase in microbial population might be responsible for increase in SMB-P both under lantana addition and fertilizer application.

Sulphur

Active pools

Available-S content ranged from 10.10 kg ha^{-1} under no lantana addition along with 33 per cent of RD to 22.00 kg ha^{-1} under 30 t ha^{-1} along with 100 per cent of RD in surface depth (Table 4.16). The corresponding values for these two treatments with respect to available-S was 6.50 and 19.25 kg ha^{-1} in

subsurface soil depth, respectively. On an average, 15.3 kg ha^{-1} available-S was observed in surface depth and 11.6 kg ha^{-1} in subsurface soil depth. Thus, subsurface soil depth had about 24 per cent less available-S in comparison to surface soil depth (Hariram *et al.,* 1993 and Trivedi *et al.,* 1998). Individually, successive increments in lantana addition increased available-S significantly and consistently in subsurface soil depth, whereas, in surface soil depth each successive increment in lantana increased available-S content significantly only over no lantana addition. Similarly, the application of fertilizer at 66 and 100 per cent of RD increased available-S content significantly and consistently in subsurface soil depth but in surface depth only 100 per cent of RD resulted into significant increase in available-S over 33 per cent of RD. The increase in available-S content with addition of lantana and fertilizer application could be because of substantial amount of S in lantana twigs which over the years has resulted in build of available-S in the present study. The interaction between lantana addition and fertilizer application on available-S was found significant in both the soil depths. In surface depth the application of fertilizer at 66 and 100 per cent of RD did not affect available-S content without lantana addition, however, with lantana addition from 10 to 30 t ha^{-1} while 66 per cent of RD was not capable of increasing available-S significantly, the 100 per cent of RD increased it significantly over its 33 per cent dose. Similarly, lantana addition at the rate of 10 t ha^{-1} while did not affect available-S significantly at any level of fertilizer application, its addition at the rate of 20 and 30 t ha^{-1} increased available-S significantly over no lantana addition. Almost similar effect of lantana addition and fertilizer application on available-S was observed in subsurface soil depth.

Irrespective of lantana addition and fertilizer application, the average WS-S content was 1.76 mg kg^{-1} in surface soil depth and 1.34 mg kg^{-1} in subsurface soil depth (Table 4.17). This indicates about 24 per cent reduction in subsurface soil depth in comparison to surface soil depth. The average content of WS-S towards available-S was found to the order of 26 per cent in both the soil depths. The interaction between lantana addition and fertilizer application on WS-S was not found significant in any of the soil depths. However, increasing levels of lantana addition, irrespective of fertilizer application and increasing levels of fertilizers, irrespective of lantana addition, increased WS-S significantly and consistently. This increase in WS-S in the present study could be because of additional increase in SOM under lantana addition as well as sulphur by way of lantana addition, which might have helped in release of sulphate S from SOM by chemical hydrolysis at elevated pH (Freney and Stevenson, 1966).

Like available-S as well as WS-S, the SMB-S ranged from a minimum value of 4.03 mg kg^{-1} without lantana addition and 33 per cent of RD to a maximum value of 6.85 mg kg^{-1} under 30 t ha^{-1} lantana addition and 100 per cent of RD in surface depth (Table 4.18). The respective values for these two treatments with respect to SMB-S in subsurface soil depth were 2.26 and 4.26 mg kg^{-1}. On an average, the SMB-S was 5.34 and 4.29 mg kg^{-1} in surface and subsurface soil depths, respectively. This indicates about 20 per cent decrease in SMB-S in subsurface depth in comparison to surface soil depth. In contrast to SMB-N and SMB-P, the SMB-S constituted about 2/3rd of available-S in both the soil depths. Like available-S, increasing levels of lantana addition and fertilizer

application increased SMB-S significantly in both the soil depths. The increase being about 19, 35 and 47 per cent in surface depth and 30, 55 and 74 per cent in subsurface depth under 10, 20 and 30 t ha^{-1} lantana addition, respectively. Since lantana addition over last 17 years has increased OM of the soils significantly which, inturn, resulted into higher microbial count. This increase in microbial count seems to be responsible for higher content of SMB-S under lantana addition. Same was also found true under increased fertilizer application as there was more crop residues and biomass turn over into the soil (Brady and Weil, 2002). The interaction between lantana addition and fertilizer application, was found significant in both the soil depths. Lantana addition under all levels of fertilizer application increased SMB-S significantly and consistently. However, fertilizer application were found to be effective in increasing SMB-S only in the presence of added lantana whereas in absence of lantana, increasing fertilizer levels did not influence SMB-C significantly. This clearly indicates supplementary effect of lantana addition and fertilizer application on SMB-S in the present study.

Passive pools

The interaction between lantana addition and fertilizer application was not found significant either on HA-S and FA-S. However, lantana addition from 10 to 30 t ha^{-1} as well as fertilizer application from 66 to 100 per cent of the RD increased HA-S as well as FA-S significantly and consistently. The range of variations in HA-S was from 0.22 to 0.52 per cent in surface depth and from 0.12 to 0.24 per cent in subsurface soil depth. Similarly, the range of variation in FA-S was from 0.15 to 0.32 per cent in surface depth and 0.10 to 0.19 per cent in subsurface soil depth. In the present study, the continuous addition of lantana

over the years has resulted into significant build-up of passive pools of OC in the soil which, in turn, was responsible for increased amount of passive pools of S under higher levels of lantana addition. The S is found in specific amino acids forms viz. cystene, cystiene and methionine and these forms are strongly bound with humus (Kononova, 1996). Therefore, the more humified material would contain more sites for S containing amino acids, thereby, resulting in higher content of HA and FA-S under lantana addition.

5.4 Chemical Environment of Soils

The chemical environment of soils has been studied with respect to available nutrients (N, P, K, S, Fe, Mn, Zn and Cu), OC and pH. The results with respect to N, P, S and OC have already been discussed. In this section the data pertaining to soil pH, available-K and DTPA extractable Fe, Mn, Cu and Zn has been discussed.

Soil pH

The application of fertilizer from 66 to 100 per cent of the RD did not influence soil pH significantly in both the soil depths (Table 4.23). However, continuous addition of lantana from 1988 increased soil pH significantly in both the soil depths in comparison to no lantana addition. The absolute increase in soil pH was from 5.48 without lantana addition to 5.67 with 30 t ha^{-1} lantana addition in surface soil depth. The corresponding value of soil pH in subsurface soil depth was 5.82 and 6.03, respectively. Lantana additions were made every season to the rice crop since 1988 and as such, the previously added lantana might have decomposed over the years and resulted in the release of bases into the soil solution. These bases in turn, might have contributed for the increase in

soil pH in the present study. In general, the soil pH was higher in subsurface soil depth in comparison to surface soil depth which might be due to the extensive leaching of bases under the influence of higher rainfall. Similar increase in soil pH have also been reported earlier due to the addition of organic material (Sharma *et al.,* 1987; Sood, 1991; Sharma, 1996).

Available potassium

The available-K content varied from a minimum value of 231.4 to a maximum value of 465.8 kg ha^{-1} in surface depth and from 215.7 to 285.2 kg ha^{-1} subsurface soil depth (Table 4.24). In general, the application of fertilizers from 66 to 100 per cent of RD increased available-K content significantly and consistently in surface soil depth, whereas, in subsurface soil depth, there was no significant effect on available-K content. The added lantana has been observed to increased the available-K content significantly and consistently in both the soil depths. The increase in available-K content with 10, 20 and 30 t ha^{-1} lantana addition over its control was about 10, 17 and 33 per cent in surface depth and 10, 17 and 26 per cent in subsurface soil depth, respectively. The build-up in available-K content in soils due to the addition of OM alone have also been reported by many workers (Nimze and Seth, 1988; Bhardwaj and Omanawar, 1994; Sharma, 1996).

DTPA-Fe

Individually, the addition of lantana increased DTPA-Fe content significantly and consistently in both the soil depths. However, increased levels of fertilizer application decreased the DTPA-Fe significantly (Table 4.25). The absolute values of DTPA-Fe increased from 8.13 mg kg^{-1} without lantana

addition to 9.80, 11.98 and 14.12 mg kg^{-1} under 10, 20 and 30 t ha^{-1} lantana addition, respectively, in surface depth. The respective values in subsurface depth were 7.81, 9.77, 11.73 and 13.95 mg kg^{-1}. As against this, the decrease in DTPA-Fe was from 11.45 at 33 per cent of RD to 10.93 and 10.65 mg kg^{-1} at 66 and 100 per cent of RD in the surface layer. Inspite of an increase in soil pH under different levels of lantana addition, the increase in DTPA-Fe might be because of external addition of Fe by way of continuous addition of lantana. In general, DTPA-Fe content was less in subsurface in comparison to surface soil depth. The interaction between lantana addition and fertilizer application was not found significant in any of the soil depths.

DTPA-Mn

Like DTPA-Fe, the content of DTPA-Mn showed a significant and consistent increase with increasing levels of lantana addition (Table 4.26). The per cent increase being 32, 53 and 88 in surface depth and 17, 38 and 58 in subsurface soil depth at 10, 20 and 30 t ha^{-1} lantana addition, respectively. Conversely, the increasing levels of fertilizer decreased DTPA-Mn significantly in both the soil depths over 33 per cent of fertilizer dose. The average DTPA-Mn in surface and subsurface soil depths were 10.71 and 9.14 mg kg^{-1} indicating a decrease of about 15 per cent in its content in subsurface soil depth. This could again be because of long-term addition of Mn through lantana addition. The interaction between lantana addition and fertilizer application was not found significant in any of the soil depths.

DTPA-Cu

In general, DTPA-Cu varied from a minimum value of 0.96 mg kg^{-1} with no lantana addition and 33 per cent of RD to a maximum value of 1.24 mg kg^{-1} with 30 t ha^{-1} lantana addition along with 100 per cent of RD in the surface depth (Table 4.27). The continuous addition of lantana from 10 to 30 t ha^{-1} resulted into significant increase in DTPA-Cu in both the soil depths. The increase in surface depth was from 0.97 mg kg^{-1} under no lantana addition to 1.06, 1.17 and 1.23 mg kg^{-1} under 10, 20 and 30 t ha^{-1} lantana addition, respectively. The corresponding values in subsurface depths were 0.78, 0.89, 0.97 and 1.05 mg kg^{-1}, respectively. The average content of DTPA-Cu was 1.11 mg kg^{-1} in surface depth and 0.29 mg kg^{-1} in subsurface soil depth, respectively. In the same study (Sharad, 1997) increased levels of lantana addition has been reported to increase different fractions of Cu in the soils which ultimately was responsible for higher levels of DTPA-Cu under lantana addition. The increase in DTPA-Cu content with application of organic materials have also been reported earlier (Singh *et al.*, 1992; Verma and Bhagat, 1992). The increasing levels of fertilizer application did not influence DTPA-Cu significantly in any of the soil depth. Similarly, the interaction between lantana addition and fertilizer application was also found not significant on DTPA-Cu in both the soil depths.

DTPA-Zn

The DTPA-Zn varied from 0.60 to 0.71 mg kg^{-1} in surface depth and from 0.52 to 0.64 mg kg^{-1} in subsurface soil depth, respectively (Table 4.28). Individually, the increasing levels of fertilizer application decreased DTPA-Zn

significantly in both the soil depths. As against this, the addition of lantana at the rate of 10 t ha^{-1} was not capable of influencing DTPA-Zn content significantly in the surface depth. However, the addition of lantana at the rate of 20 and 30 t ha^{-1}, increased significantly DTPA-Zn content. In subsurface soil depth, the addition of lantana right from 10 to 30 t ha^{-1} increased DTPA-Zn significantly and consistently. Sharad (1997) has reported an increase in almost all the Zn fractions under different levels of lantana addition in the same experiment. The increase in all these fractions over a period of time might have contributed to DTPA-Zn under different levels of lantana addition in the present study.

5.5 Microbial Environment of soils

Microorganisms play an important role in nutrient transformation in soils and thus, these studies are important to know the fertility and productivity of the soils. The effect of different levels of lantana addition and fertilizer application on microbial count in terms of bacteria, fungi and actinomycetes were studied under long-term experiment and the results are discussed as under:

Bacteria

Lantana addition irrespective of fertilizer application and fertilizer application irrespective of lantana addition, increased bacterial count significantly and consistently in both the soil depths (Table 4.20). The bacterial population under 0, 10, 20 and 30 t ha^{-1} lantana addition was found to the order of 14.88, 21.66, 41.77 and 55.11 cfux10^5 g/soil in surface depth and 9.55, 14.78, 27.33 and 38.55 cfux10^5 g/soil in subsurface depth, respectively. Similarly, the bacterial population under 33, 66 and 100 per cent of RD was found to the tune of 27.33,

33.91 and 38.83 cfux10^5 g/soil in surface depth and 19.00, 21.58 and 27.08 cfux10^5 g/soil in subsurface soil depth, respectively. The addition of lantana as well as the application of fertilizer provided favourable environment for the bacterial growth due to moderating soil pH and better substrate available to bacteria (Malewar *et al.*, 1999). In general, the bacterial population was found about 1.3 times less in subsurface soil depth in comparison to surface soil depth. This might be because of the fact that lantana is being continuously added only in surface depth since last 17 years and major portion of organic carbon which is substrate to bacteria was also found only in surface depth.

The interaction between lantana addition and fertilizer application on bacterial population was found significant only in surface soil depth. The application of 66 per cent of RD did not influence bacterial population either without lantana addition or with lower level of lantana (10 tha^{-1}). However, the addition of fertilizer from 66 to 100 per cent of RD increased bacterial population over 33 per cent of RD significantly and consistently under higher levels of lantana addition (20 to 30 t ha^{-1}). Similarly, the lower levels of lantana at the rate of 10 t ha^{-1} did not increase bacterial population significantly under 33 per cent of RD, however, lantana addition right from 10 to 30 t ha^{-1} increased bacterial population under 66 and 100 per cent of RD.

Fungi

The population of fungi in the surface soils ranged from 35.66 cfux10^5 g/soil under no lantana addition alongwith 33 per cent of RD to 59.66 cfux10^5 g/soil under 30 t ha^{-1} lantana addition alongwith 100 per cent of RD (Table 4.21).

The corresponding values under these two treatments in subsurface soil depth were 15.00 and 37.66 cfux10^5 g/soil. The average values for population of fungi in surface and subsurface soil depths were 47.8 and 28.5 cfux10^5 g/soil, respectively, indicating, a decrease of about 1.3 times which was almost the same as observed for the bacterial population. Individually, lantana addition as well as fertilizer application, increased fungi population significantly in both the soil depths. The increase being 13, 29 and 40 per cent in surface depth and 20, 39 and 49 per cent in subsurface soil depth under 10, 20 and 30 t ha^{-1} lantana addition in comparison to no lantana addition. The per cent increase in fungi population under 66 and 100 per cent of RD over its 33 per cent dose were 9 and 25 in surface and 28 and 45 in subsurface soil depth, respectively. Due to saprophytic nature of fungi, high availability of dead and decomposed OM content under higher levels of lantana addition and fertilizer application and its moderating effect on soil pH, probably favoured the high fungal population (Deb, 1990; Malewar *et al.,* 1999). The interaction between lantana addition and fertilizer application on population of fungi was not found significant in any of the soil depths.

Actinomycetes

Irrespective of fertilizer application, increasing levels of lantana increased actinomycetes population from 16.44 to 36.00 cfux10^5 g/soil in surface depth and from 12.22 to 24.25 cfux10^5 g/soil in subsurface depth, respectively (Table 4.22). Similarly, increasing levels of fertilizer application also increased actinomycetes population significantly and consistently in both the soil depths. The higher OM build up as well as nutrient availability under lantana addition as

well as under fertilizer application might have favoured the actinomycetes growth. This contention was further collaborated with the fact that actinomycetes population in subsurface depth was about 1.4 times less in comparison to surface depth due to less build-up in OM content. The interaction between lantana addition and fertilizer application was also found significant in both the soil depths. Without lantana addition, only 100 per cent of RD increased actinomycetes count over its 33 per cent dose. However, when lantana was added from 10 to 30 t ha^{-1}, the application of both 66 and 100 per cent of RD increased actinomycetes count significantly in both the soil depths. Similarly at lower levels of fertilizer application (33 per cent of RD), the addition of lantana at the rate of 10 t ha^{-1} was not found capable of increasing actinomycetes count significantly whereas 20 and 30 t ha^{-1} lantana resulted in significant increase in actinomycetes count even under this level of fertilizer application. Conversely, the lantana addition right from 10 to 30 t ha^{-1} increased actinomycetes significantly and consistently under 66 and 100 per cent of RD in both the soil depths.

5.6 Physical Environment of soils

Physical environment of the soils was studied in light of bulk density and saturated hydraulic conductivity as affected by long-term lantana addition and fertilizer application.

Bulk density (BD)

Bulk density (BD) signifies the quantity of pore space as well as soil solids. Soils with sandy texture generally have higher BD while the finer particles soils such as silt loam, clay loam and clays have low BD and exhibit an excellent

soil tilth for better root proliferation and nutrient absorption. The BD values determined at 0-0.15 to 0.15-0.30 m soil depths showed considerable decrease with increasing levels of lantana addition (Table 4.1). This decrease in BD values were found significant upto the addition of 20 t ha^{-1} lantana in surface depth and upto 30 t ha^{-1} in subsurface soil depth. The increasing levels of fertilizer application, however, did not influence BD values significantly in any of the soil depths. The decrease in BD values were observed from 1.21 to 1.10 Mgm^{-3} in surface depth and from 1.30 to 1.12 Mgm^{-3} in subsurface soil depth with increasing levels of lantana addition. The decrease in BD values under higher levels of lantana addition could be ascribed to increased SOM content emanating from the added lantana over a period of 17 years. These findings are in close conformity with those of Bhatnagar *et al.* (1992) and Mishra and Sharma (1997). This decrease in BD values under above mentioned treatments must be responsible for improved granulation and porosity of soil as has also been reported by Chandravamshi *et al.* (1999). Bulk density values were higher at deeper soil layers which apparently resulted from lower content of SOM and less aggregation and root penetration (Brady and Weil, 2002). There was no interaction between lantana addition and fertilizer application in BD in any of the soil depths.

Saturated hydraulic conductivity (SHC)

In general, the SHC ranged from 0.0143 Ks cm/min under no lantana addition to 0.0242 Ks cm/min under 30 t ha^{-1} lantana addition in surface depth (Table 4.2). The corresponding values in subsurface soil depth were 0.0008 and 0.0046 Ks cm/min. This increase in SHC under increasing levels of lantana

addition could be ascribed to significant build-up in OM and subsequent increase in porosity of the soil. Similar results with organic amendments has also been reported by Bellaki *et al.* (1998). In the present study the addition of fertilizer from 33 to 100 per cent of the RD did not influence SHC significantly. The interaction between lantana addition and fertilizer application was also not found significant on SHC in any of the soil depths.

5.7 Rice and Wheat Productivity

The data given in Tables 4.32 to 4.35 indicates that increasing levels of fertilizer increased the grain and straw yield of rice and wheat significantly and consistently during both the years of study. The increase in grain yield of rice at 66 and 100 per cent of the RD over its 33 per cent of dose was about 27 and 31 per cent during 2004 and 26 and 37 per cent during 2005, respectively. The corresponding increase in straw yield of rice were 33 and 42 per cent during 2004 and 20 and 32 per cent during 2005 under 66 and 100 per cent of RD over its 33 per cent dose. Similarly, the increase in grain yield of wheat at 66 and 100 per cent of RD amounted to about 9 and 16 per cent during 2004-05 and 7 and 13 per cent during 2005-06 over its 33 per cent dose, respectively. The increase in straw yield of wheat at these two levels of fertilizer application were about 15 and 23 per cent during 2004-05 and 14 and 20 per cent during 2005-06, respectively. The beneficial role of fertilizer in increasing crop yields is well documented in theory as well as in practice. Substantial responses of fertilizer application to different crops in different agro-ecosystem have also been reported earlier (Singh, 1994; Verma and Dixit, 1989; Sharma, 1996; Sharad, 1997).

The continuous addition of lantana every year over the last 17 years before rice transplanting of rice has also increased the grain and straw yield of rice and wheat during both the years of experimentation (Tables 4.32 to 4.35). Lantana addition at the rate of 10, 20 and 30 t ha^{-1} over the control increased the grain yield of rice by about 8, 28 and 32 per cent during 2004 and 10, 33 and 37 per cent during 2005, respectively. The increase in straw yield of rice at these three levels of lantana were about 10, 32 and 38 per cent during 2004 and 13, 37 and 40 per cent during 2005, respectively. Similarly, the increase in grain yield of wheat at 10, 20 and 30 t ha^{-1} lantana addition was about 12, 21 and 25 per cent during 2004-05 and 8, 17 and 18 per cent during 2005-06. The increase in straw yield at these three lantana levels was about 20, 37 and 47 per cent during 2004-05 and 15, 28 and 32 per cent in 2005-06, respectively. The substantial increase in rice and wheat yields with the addition of lantana could partially be attributed to improvement in all the pools of C (active, slow and passive) and nutrients (active and passive). In addition to this, the build-up of OM also increased WSAC and aggregate porosity (Sharma *et al.,* 1995) as well as increased SHC (Table 4.2) and decrease in BD (Table 4.1). Improvement in OM content due to lantana addition has also been reported to be responsible for decrease in clod breaking strength of soils (Sharma *et al.*, 1995). The improvement in these physical properties of soils is particularly helpful in increasing the wheat yield following rice (Sharma *et al.,* 1995). Improved physical condition of the soils favoured the growth and multiplication of soil organisms (Table 4.20 to 4.22), essential for the mineralization of OM. The cumulative effect of lantana biomass on all these

properties seems to have resulted in significant growth of crop plants compared with those growing in plots without lantana. Similar results on the crop yields with lantana addition have also been reported earlier (Singh and Thakur, 1990; Bhardwaj and Kanwar, 1991; Sharma, 1996).

The interaction between lantana addition and fertilizer application was found significant on grain and straw yield of rice and wheat during both the years of study (Table 4.32 to 4.35). Lantana addition from 10 to 30 t ha^{-1} increased rice and wheat grain yield significantly and consistently when added under low levels of fertilizer application (33 per cent). However, under higher levels of fertilizer application (66 and 100 per cent of RD), lantana addition only upto 20 t ha^{-1} was found to increase rice and wheat grain yield significantly and consistently. Further increase to 30 t ha^{-1} lantana addition did not improve rice and wheat grain yield significantly during both the years. Similar to grain yield of rice and wheat, the lantana addition from 10 to 30 t ha^{-1} increased straw yield of these crops significantly under low levels of fertilizer application (33 per cent of RD). However, under higher levels of fertilizer application (66 and 100 per cent of RD), lantana addition only upto 20 t ha^{-1} resulted in significant increase in straw yield of rice and wheat as further increase in its addition did not improve straw yield of these crops over 20 t ha^{-1} lantana addition. This clearly indicates that higher addition of lantana (30 t ha^{-1}) under higher levels of fertilizer application was not capable of increasing rice and wheat productivity significantly. Fertilizer application at 66 and 100 per cent of RD over 33 per cent of RD increased significantly grain and straw yields of rice and wheat in the absence as well as in the presence of only lower levels of lantana addition (10 t ha^{-1}) during both the

years of study. However, under higher levels of lantana addition (20 to 30 t ha^{-1}), the fertilizer application at the rate of 66 and 100 per cent of the RD did not increase grain and straw yields of rice and wheat significantly in both the years. The non responsiveness of higher levels of fertilizer application under higher levels of lantana addition clearly indicates that lantana addition over the last 17 years has substantially increased all the pools of OC and nutrients as well as physical and microbiological properties of soils and as such, there was higher availability of the nutrients to the crops even under lower levels of lantana addition. It is worthwhile to mention here that grain yield of rice produced under 100 per cent of RD without lantana addition (3.37 and 3.45 Mg ha^{-1} during 2004 and 2005, respectively) was at par with that produced with 30 t ha^{-1} lantana addition along with 33 per cent of RD during both the years (3.50 and 3.43 Mg ha^{-1} during 2004 and 2005, respectively). similarly, the grain yield of wheat produced with 100 per cent of RD without lantana addition (3.34 and 3.35 Mg ha^{-1} during 2004-05 and 2005-06 respectively), was almost at par with that produced under 33 per cent of RD along with 20 t ha^{-1} lantana addition (3.33 and 3.41 Mg ha^{-1} during 2004-05 and 2005-06, respectively). This indicates a substitution of fertilizer to the extent of 66 per cent of the RD to both rice and wheat grown in a sequence alongwith higher levels of lantana addition (20 and 30 t ha^{-1}) over the years. However, lower levels of lantana addition (10 t ha^{-1}) could save only 33 per cent of the RD. Such beneficial effects of combined use of organic manures and inorganic fertilizers on crop yield have also been reported by many workers (Sharma and Bali, 1998; Singh and Verma, 1999; Katiyal and Ganghwar, 2000; Singh *et al.*, 2001).

5.8 Nutrient Uptake

The interaction between lantana addition and fertilizer application was not found significant on the uptake of nutrients (N, P and S) both in rice and wheat during both the years of study. Therefore, the results of main effects are discussed in this section.

A reference to the data in Table 4.36 and 4.37, indicates that addition of lantana from 10 to 30 t ha^{-1} increased the uptake of N, P and S significantly over no lantana addition by both the crops during both the years. The per cent increase in uptake by rice was 9.0, 21.2 and 27.4 per cent in N; 31.2, 47.4 and 61.7 per cent in P; and 30.5, 52.0 and 65.7 per cent in S under 10, 20 and 30 t ha^{-1} lantana addition over the control during the year 2004. The respective per cent increase in the uptake of these nutrients during 2005 was 7.4, 28.0 and 37.6 in N; 31.8, 63.6 and 82.1 in P; and 25.3, 60.5 and 81.5 in S, respectively. Similarly, the per cent increase by wheat was 19.4, 26.7 and 32.7 in N; 8.3, 12.9 and 18.4 in P; and 19.2, 42.4 and 51.4 in S, under 10, 20 and 30 tha^{-1} lantana addition, during 2004-05. Almost similar increases were also observed in N, P and S uptake by wheat during 2005-06. The application of fertilizer at the rate of 66 and 100 per cent also resulted in significant increase in N, P and S both by rice and wheat during both the years of study. The per cent increase in N, P and S uptake at these two levels of fertilizer application over its 33 per cent dose was 11.9 and 19.9 in N; 51.2 and 58.7 in P; and 37.4 and 60.2 in S during 2004, respectively. The corresponding increase during 2005 was 21.6 and 30.5 in N; 70.5 and 86.3 in P; and 42.5 and 76.6 in S, respectively. The per cent increase in

uptake by wheat under 66 and 100 per cent of RD was 13.1 and 18.8 in N; 3.9 and 12.5 in P; and 29.9 and 41.3 in S during 2004-05. The corresponding values for increase in N, P and S uptake during 2005-06 under 66 and 100 per cent of RD were 14.9 and 20.1, 6.0 and 12.1 and 23.6 and 34.6, respectively. As discussed earlier, the fertilizer application responded significantly in increasing the yield of rice and wheat during both the years which, in turn, was responsible for the significant higher uptake of the nutrients by these crops. Similar results have also been reported earlier (Nair and Gupta, 1999; Tiwari *et al.,* 1995). The increased uptake of N, P and S by rice and wheat under the increased levels of lantana addition may be attributed to increase in their availability in the soils as has also been reported in earlier section. Besides this, better proliferation of roots under the influence of lantana addition might have resulted in increased absorption of nutrients by wheat from larger areas and greater depths. Moreover, uptake of nutrients almost followed the yield pattern. Almost similar increase in N, P and S uptake upon the addition of organic materials have also been reported in the literature (Verma, 1991; Sharma, 1992; Brar *et al.,* 1995; Singh *et al.,* 2001).

5.9 Relationship between SOM Pools, Crop Productivity and Nutrient Supply

5.9.1 Relationship of SOM Pools with Crop Productivity

All except one (slow pool, 2-1 mm) SOM pools had significant and positive relationship with the productivity of rice and wheat (Table 4.38 and 4.42). The relative contribution of different SOM pools towards crop productivity were also computed (Table 4.39 and 4.43). The WS-CHO was the most important active pool of SOM contributing towards rice and wheat productivity. The R^2

values indicates that about 80 and 79 per cent variations in rice and wheat yield was explained by this WS-CHO, respectively. The second most important variable contributing to the total variations in the regression of rice and wheat grain yield was SMB-C. The total variations in rice and wheat grain yield explained by these two SOM pools was about 87 and 84 per cent. The importance of WS-CHO and SMB-C towards crop productivity might be attributed to the fact that WS-CHO in the soil accounts for 1/10th of the SOC (Kononova, 1996). Furthermore, WS-CHO also have crucial role in the formation and stabilization of soil structure through the action of polysaccharide (Martin, 1945; Cheshire, 1979). Thus, improvement in physical properties of soils leads to better crop growth and higher crop productivity. Microbial-C is also important source of bio-energy to microorganisms that ultimately help to stabilize the soil structure for optimum crop growth. Slow and passive pools of SOM were found to be little contributors to the crop productivity due to their resistance to decomposition and mineralization (Brady and Veil, 2002).

5.9.2 Relationship between SOM Pools with Nutrient Supply

Like the relationship between SOM pools and crop productivity, WS-CHO had the significant and positive relationship with nutrient supply in terms of N, P and S both to rice and wheat (Table 4.38 and 4.42). To find out the relative contribution of different pools to nutrient supply to rice and wheat, linear stepwise regression equations were computed (Table 4.39 and 4.43). From the order of relative importance of independent variables, it is evident that the most important variable contributing to the total variations in the regression of N, P and S uptake

was WS-CHO both in rice and wheat crops. The second most important variable was SMB-C in the uptake of P and S and WS-OC in case of N uptake both by rice and wheat crop. The total variations explained by these parameters in the uptake of P and S was 81 and 94 per cent in rice and 78 and 79 in wheat, respectively. Similarly, the total variations explained by WS-CHO and WS-OC in case of N uptake was 94 and 74 per cent in rice and wheat, respectively. This might be because of the fact that WS-CHO, SMB-C and WS-OC are the active pools of SOC in the soil and they have an important role in the formation and stabilization of soil structure through the action of bacterial polysaccharides as well as an important source of bioenergy to micro-organisms (Kononova, 1996).

5.9.3 Relationship between Nutrient Pools and Crop Productivity

A significant and positive relationship between N, P, S pools with rice and wheat grain revealed the importance of these major nutrients for better crop growth and better yield (Table 4.40 and 4.44) as has also been reported by Brady and Veil (2002).

Like soil organic pools, to assess the relative contributions of the various nutrient pools to crop productivity, linear stepwise regressions were computed for rice and wheat (Table 4.41 and 4.45). From the nutrition point of view, the most important variables among nutrient pools were SMB-P followed by SMB-N for rice productivity. The total variations in rice grain yield explained by these two nutrient pools were about 84 per cent. Similarly, the most important nutrient pool contributing to the total variations in wheat grain yield was again SMB-P followed by available-N. The total variations in wheat grain yield

explained by these two nutrients pools was about 84 per cent. The experimental soils was acidic in reaction with high P-fixation capacity and as such the improvement in the content of SMB-P might have resulted in more release of P into the soil solution which helped in better root growth and overall crop productivity. Similarly, available-N has high assimilation rate and can be used as a source of energy by soil microorganisms. These microorganisms, in turn, might have improved the soil structure and thereby crop productivity. This clearly indicates SMB-P, SMB-N and available-N as the most important nutrient pool's contributor towards rice and wheat productivity in the present study. All the nutrient pool's taken together contributed about 88 and 93 per cent variation in rice and wheat grain yield, respectively.

5.9.4 Relationship between Nutrient Pools and their Supply

All the nutrient pools (active and passive) had significant and positive relationship with N, P and S uptake both by rice and wheat crop (Table 4.40 and 4.44). This might be due to the labile nature of these nutrients fractions which are responsible for contributing to their supply to the crop plants.

To assess the relative contribution of different nutrient pools towards their supply to rice and wheat crop, the linear stepwise regressions were also computed (Table 4.41 and 4.45). For the supply of N to rice the most important nutrient pool was available-N followed by SMB-P (about 93 per cent) whereas for the supply of P, available-P was the most important nutrient pool followed by SMB-N (79 per cent). Similarly, for the supply of S to rice crop, SMB-S was the most important nutrient pool followed by SMB-P (91 per cent). As far as supply of N to wheat crop was concerned, it was found that available-N was the most

important nutrient pool followed by SMB-N (about 72 per cent). For the total P-uptake by wheat, available-P was the most important pool of nutrient followed by available-N (about 76 per cent) whereas, for total S-uptake, SMB-S was the most important nutrient pool followed by available-S (about 78 per cent). The contribution of these nutrient pools towards their supply to rice and wheat is quite understandable as all these nutrient pools are labile pools and contributed significantly towards their supply to these crops. In addition to this, these nutrients are also utilized by soil microorganisms for their multiplication which ultimately resulted into better soil structure and root proliferation and ultimately for better crop yield and efficient nutrient absorption. As far as the contribution of passive pools of nutrients was concerned, it was observed that they have very little contribution towards nutrient supply in present study which could be because of their resistant nature for their decomposition and mineralization.

5.10 Inter-Relationships between C-Pools

To find out the inter-relationship among different SOM pools, simple coefficient of correlations 'r' (Table 4.46) as well as linear stepwise regression equations were worked out (Table 4.47). There was strong association among active Vs slow, slow Vs passive and active Vs passive pools of SOM, as the values of 'r' among all these pools were significant and positive. However, WS-OC was found to bore highest association with almost all the slow pools followed by WS-CHO. Similarly, among passive pools, HA-C had invariably higher values of 'r' with all the slow pools in comparison to FA-C. As far as association between active Vs passive pools was concerned, it was noticed that WS-CHO had strongest association both with HA and FA-C followed by WS-OC.

Linear stepwise regression equations among active and slow, active and passive and passive and slow C pools were also computed to see their relative contributions to each other (Table 4.47). The most important active pool of C was found to be WS-OC followed by WS-CHO and SMB-C to all the slow fractions of SOC (> 2 mm to < 0.25 mm). The R^2 value indicate that about 66, 34, 45, 39 and 66 per cent variations in C-associated with soil size fractions of > 2 mm, 2-1 mm, 1-0.5 mm, 0.5-0.25 mm and < 0.25 mm could be explained by these three active pools of SOC. When association between slow pools of SOC was studied, it was found that C associated only with three coarser soil size fractions (> 2 mm, 2-1 mm and 1-0.5 mm) was found to contribute towards HA and FA-C whereas, the C-associated with the finer soil size fractions was not found to contribute to passive pools of SOC. Among active pools, WS-CHO was the most important followed by SMB-C to explain variations in HA and FA-C in the soil. The total variations explained by these two active pools was about 69 per cent to HA-C and about 70 per cent to FA-C. This clearly indicates that upon exhaustion of active pools of C there is slow and steady transformation of C from its slow and passive pools to active pools meaning thereby that build-up in any pool of C through organic amendments in the soils is beneficial for maintaining soil fertility and crop productivity on sustainable basis.

5.11 Validation of Carbon Models

5.11.1 Roth-C Model

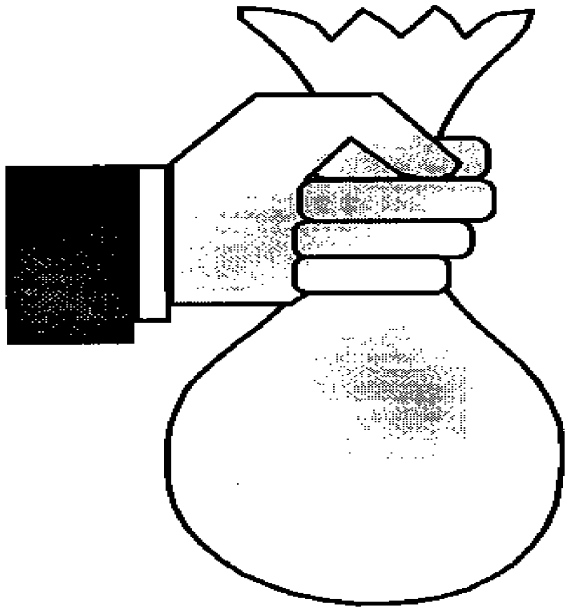
The dynamics of carbon in the soil is very complex in nature. Therefore, the models simulating these dynamic processes can also be complex too. Soil carbon simulation models are process oriented multi-compartment models. GCTE-SOMNET has made an attempt to simplify the carbon models and Roth-C-26.3 carbon model is one among them.

Roth-C-26.3 is a model of turn over of organic carbon in non-waterlogged soils that allows for the effect of soil type, temperature, moisture content and plant cover on the turn over process. It uses the monthly time step to calculate total organic carbon and microbial biomass C on a time scale of years to centuries (Jenkinson *et al.,* 1992). It needs few inputs which are easily available and discussed in chapter III. Roth-C-26.3 model was used to compare the changes in SOC with its measured content under different levels of lantana addition and fertilizer application in a long-term rice-wheat cropping system. The prediction of Roth-C-26.3 model for SOC content passed nearly through the observed values over the last 17 years. The yearly input of plant residues carbon calculated by the model in reverse mode might be responsible for this close association. Similar plausible fit between the simulated and observed SOC was also observed by Coleman *et al.* (1997). Irrespective of fertilizer application, the best fit between simulated and observed SOC in the present study was observed under no lantana addition with RMSE values of 0.30 to 0.74 (Fig. 4.2). Similarly, the RMSE values from 2.76 to 3.23 under 10 t ha^{-1} lantana addition also indicated good association between simulated and observed SOC content in soil (Fig 4.3). It is interesting to note that as the levels of lantana addition increased from 20 to 30 t ha^{-1}, the association between simulated and observed SOC decreased to some extent. The RMSE values ranged from 3.77 to 4.38 under 20 t ha^{-1} lantana addition (Fig. 4.4) and from 4.33 to 4.86 under 30 t ha^{-1} lantana addition (Fig. 4.5). This clearly indicates that as the continuous addition of carbon to the soil increased, the difference between simulated and observed SOC was

also increased. However, looking into the overall association between simulated and observed SOC under the different twelve treatment combinations of four levels of lantana and three levels of fertilizer application, it could be said that Roth-C-26.3 model could very well be used for the prediction of build-up of OC in soils even under temperate conditions.

5.11.2 Carbon and Nitrogen Dynamics (CANDY) Model

The carbon and nitrogen dynamics (CANDY) model could not be used for want of data input required in running the model.



Summary

Chapter VI

SUMMARY

Sustained soil productivity for a profitable agriculture involves rotational and multiple cropping with high yielding varieties, application of fertilizers and manures etc. and above all, soil conditions to withstand and favourably support the various agricultural practices. A sound approach towards sustainable food production requires proper assessment of the direct, residual and commulative effective of various inputs over a period of time on crop yield as also the soil conditions – physical, chemical and biological. This further warrants taking care against any nutrient element, suddenly becoming deficit or excessive due to rapid absorption or antagonistic interaction in the soil-plant system because of injudicious use of inputs.

With this background, the experiment under rice-wheat cropping system with treatments of lantana addition and fertilizer application, constituted an ideal basis to assess the sustainable use of soil and sustainability of farming system. Therefore, the present study entitled as "Carbon sequestration and nutrient dynamics in a long-term lantana amended soil under rice-wheat system" in randomized block design with twelve treatments combination of four levels of lantana addition and three levels of fertilizer application replicated three times, was under taken from *Kharif* 2004 to *Rabi* 2005-06 at the experiment farm of Department of Soil Science, College of Agriculture, CSK HPKV, Palampur. The experiment was in operation since *Kharif* 1988. The soils of the experimental site

were acidic in reaction and classified taxonomically as 'Typic Hapuldalfs'. Soil samples taken from 0-0.15 and 0.15-0.30 m soil depth after the harvest of wheat (*Rabi* 2004-05) were analyzed for physical, chemical and biological parameters using standard methods. Besides this, different pools of C, N, P and S were also studied. The rice and wheat yield from *Kharif* 2004 to *Rabi* 2005-06 and nutrient uptake data was also recorded and correlated with different pools of organic carbon, N, P and S and inter-relationships among different pools of C was also worked out.

The salient findings that emerged out of present investigation are summarized as follows:

6.1 Carbon Sequestration and SOM Dynamics

- Individually, the addition of lantana and application of fertilizer increased C stocks with the advancement of time. The minimum C stock build-up was observed under no lantana addition along with 33 per cent of RD and maximum under 30 t ha^{-1} alongwith 100 per cent of RD.
- The addition of lantana at the rate of 10, 20 and 30 t ha^{-1} increased C stock ha^{-1} yr^{-1} basis by 0.25, 0.34 and 0.41 Mg in comparison to no lantana addition. Increasing fertilizer application also increased C stock ha^{-1} yr^{-1}.
- Out of total OM added over 17 years through lantana addition at the rate of 10, 20 and 30 t ha^{-1}, only about 28, 15 and 13 per cent was sequestrated in 0-0.30 m soil depth, respectively.

- Active and passive pools of carbon together accounted for about 71 per cent of the total OM retained in soils, passive pools being the highest (about 60 per cent) and active pools the lowest (about 11 per cent).
- Increasing levels of lantana addition, increased the per cent retention of C in active pools and decrease it in passive pools. Among active pools, the maximum portion was found to be retained in WS-CHO followed by SMB-C and minimum in WS-OC with average values of 4.80, 3.50 and 2.24 per cent, respectively.
- Out of average retention of 18.48 per cent of total C in 0-0.30 m, 15.7 per cent was found to be retained in surface and only 3.7 per cent was found in subsurface soil depth.
- On an average, the reduction in passive and active pools of C in subsurface soil depth was about 55 and 24 per cent, respectively in comparison to surface soil depth. All active (WS-OC, WS-CHO and SMB-C) and passive (HA-C and FA-C) pools of C were found to be higher in surface depth in comparison to subsurface soil depth.

6.2 Carbon Pools

- Lantana addition resulted in significant increase in SOC in comparison to control in both the soils depths. The per cent increase was about 30, 43 and 49 in surface layer and 12, 19 and 28 in subsurface soil depth. The average OC content in surface layer was 12.3 g kg^{-1} which was reduced to 8.6 g kg^{-1} in subsurface soil depth. The OC content of soils was not affected significantly with increasing levels of fertilizer application.

- Individually, lantana addition and fertilizer application, increased all the three active pools of C significantly in both the soil depths. The per cent increase at 10, 20 and 30 t ha^{-1} lantana addition in surface depth was observed to be 67, 127 and 196 in WS-OC; 9, 27 and 36 in WS-CHO; and 14, 31 and 57 in SMB-C, respectively.
- The C-bound to aggregate size fractions, known as WSAC was higher in 2-1 mm soil size fraction followed by > 2 mm and 1-0.5 mm in both the soil depths. The C associated with different aggregate size fractions increased with an increase in lantana addition from 10 to 20 t ha^{-1}. In general, more than 50 per cent of C was retained in aggregate size fraction from 1-0.5 and 0.5-0.25 mm, when grouped together.
- The passive pools of SOM viz; HA and FA-C significantly increased with increase in lantana addition as well as fertilizer application in both the soil depths. The HA and FA-C was about 32 per cent less in subsurface soil depth in comparison to surface soil depth.
- Among the passive pools of SOM, FA-C was slightly higher over the HA-C fraction.

6.3 Pools of N, P and S

- The available-N content increased with increasing levels of lantana addition and fertilizer application. The minimum available-N was observed under no lantana addition alongwith 33 per cent of RD and maximum under 30 t ha^{-1} lantana addition alongwith 100 per cent of RD in both the soil depths.

- Water soluble-N and SMB-N were minimum under no lantana addition along with 33 per cent of RD and maximum under 30 t ha^{-1} with 100 per cent of RD in both the soil depths. The average contribution of WS-N and SMB-N to available-N was about 9 and 43 per cent in surface depth, and 8 and 22 per cent in subsurface soil depth, respectively. Increasing levels of lantana addition and fertilizer application, increased WS-N and SMB-N significantly in both the soil depths. In general, the amount of SMB-N was about 5 times higher than WS-N.
- The passive pools of N (HA and FA-N) were the lowest under no lantana addition along with 33 per cent of RD and highest under 30 t ha^{-1} along with 100 per cent of RD. The increasing levels of lantana addition as well as fertilizer application, individually, increased HA and FA-N significantly in both the soil depths.
- The content of available, WS and SMB-P were lowest under no lantana addition alongwith 33 per cent of RD and highest under 30 t ha^{-1} lantana addition alongwith 100 per cent of RD in both the soil depths. Individually, increase in lantana addition and fertilizer application increased available-P, WS-P and SMB-P significantly in both the soil depths. On an average, the contribution of WS-P and SMB-P to available-P in surface soil depth was about 45 and 15 per cent, respectively.

- The contents of available, WS and SMB-S were minimum under no lantana addition alongwith 33 per cent of RD and maximum under 30 t ha^{-1} lantana addition alongwith 100 per cent of RD. In general, all the active pools of S were found to be in less amount in subsurface soil depth in comparison to surface soil depth. The average contribution of WS-S and SMB-S to available-S in the surface soil depth was about 26 and 66 per cent, respectively. Successive increments in lantana addition and fertilizer application, individually, increased all the active pools of S.
- Increasing levels of lantana addition as well as fertilizer application increased passive pools of S (Ha and FA-S) significantly in both the soil depths with the result the highest content of these pools were found under 30 t ha^{-1} lantana addition alongwith 100 per cent of RD.

6.4 Chemical Environment of Soils

- Addition of lantana over the last 17 years increased soil pH significantly over no lantana addition. The increase was from 5.48 under no lantana addition to 5.67 with 30 t ha^{-1} lantana addition in surface soil depth. Fertilizer application did not influence soil pH.
- Continuous lantana addition increased available-K content significantly in both the soil depths. The increase was 10, 17 and 33 per cent in surface soil depth with 10, 20 and 30 t ha^{-1} lantana addition, respectively. Fertilizer application also increased available-K in soil.

- Continuous addition of lantana over the last 17 years increased DTPA extractable micronutrients significantly over no lantana addition. Fertilizer application while did not affect the content of DTPA-Cu, decreased DTPA-Fe, Mn and Zn significantly in soils.

6.5 Microbial Environment of Soils

- Continuous lantana addition and fertilizer applications over the last 17 years, increased the population of bacteria, fungi and actinomycetes significantly in both the soil depths. The microbial population was comparatively higher in surface soil depth in comparison to subsurface soil depth.

6.6 Physical Environment of Soils

- Marked decrease in BD and an increase in SHC was observed with continuous addition of lantana over 17 years. Fertilizer application while did not influence BD values, increased SHC significantly.

6.7 Rice and Wheat Productivity

- Continuous addition of lantana and fertilizer application over the last 17 years, increased rice and wheat grain yield significantly and *consistently. The increase in rice yield at 10, 20 and 30 t ha^{-1} lantana* was 8, 28 and 32 per cent during 2004 and 10, 33 and 37 per cent during 2005, respectively over the control. The corresponding increase in wheat yield at these three levels of lantana was 12, 21 and 25 per cent during 2004-05 and 8, 17 and 18 per cent during 2005-06.

- Lantana addition upto 30 t ha^{-1}, increased rice and wheat yield significantly at 33 per cent of RD and only upto 20 t ha^{-1} at 66 and 100 per cent of RD. Similarly, fertilizer application upto 100 per cent of RD, increased rice and wheat yield significantly at zero and 10 t ha^{-1} lantana addition, whereas, at 20 and 30 t ha^{-1} lantana addition, 66 and 100 per cent of recommended fertilizer dose did not influence rice and wheat yield significantly.

6.8 Nutrient Uptake

- The nutrients uptake by both rice and wheat crops followed almost similar trend as that of their yields. Increasing levels of lantana addition and fertilizer applications resulted in highest uptake of N, P and S.

6.9 Relation between SOM pools, Crop Productivity and Nutrient Supply

- All the pools of SOM except one (slow pool, 2-1 mm-C) showed significant and positive relationship with grain yield of rice and wheat and total N, P and S uptake by these two crops.
- Step-wise regression equations indicates that the most important SOM pool contributing towards variations in rice and wheat yields and uptake of N, P and S was WS-CHO followed by SMB-C. The total variations in rice and wheat grain yield explained by these two SOM pools were 87 and 84 per cent, respectively.
- All the nutrient's pools (N, P and S) were significantly and positively correlated with rice and wheat grain yield. Step-wise regression analysis indicated SMB-P as the most important and SMB-N as the

second most important nutrient pool contributing to rice grain yield. Similarly, SMB-P was the most important and available-N, the second most important nutrient pool contributing to wheat productivity. The total variations explained in rice and wheat grain yield by these two nutrient pools were 79 and 72 per cent, respectively.

6.10 Inter-relationship between Carbon Pools

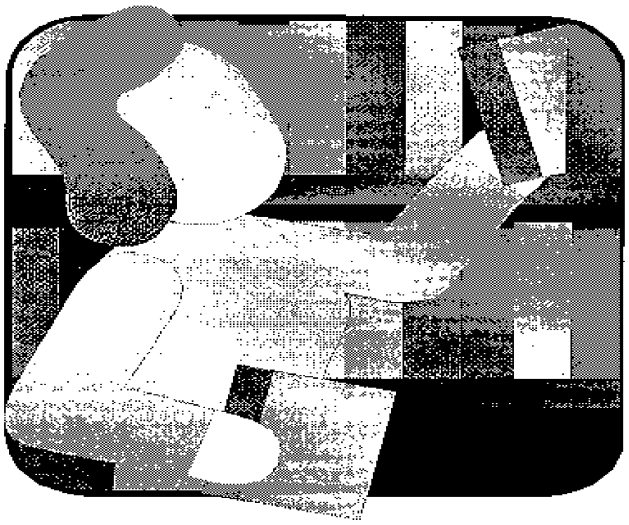
- A strong association between active vs slow, slow Vs passive and active Vs passive pools of SOM was observed in the present study.
- Regression analyses showed WS-OC as the most important and WS-CHO as the second most important active pools contributing to slow pools of OC. Similarly, WS-CHO was the most important and SMB-C as the second most important pool of SOM contributing towards total variations in passive pools of OC. The C-associated only with greater than 0.5 mm soil size fraction was found to be the most important slow pools of SOM related to passive pools of SOM in the present study.

6.11 Validation of Carbon Models

- The prediction of simulated SOC content made by Roth-C-26.3 carbon model was almost similar to that of measured content for all the twelve treatments combination of four levels of lantana addition and three levels of fertilizer application. Hence, this model can be used for prediction of SOC in the coming years. However, CANDY model could not be used for want of required input data to run the model.

CONCLUSION

- Out of the total OM added through lantana addition from 10 to 30 t ha^{-1} over the last 17 years, the average sequestration in the soil was only about 19 per cent in 0-0.30 m soil depth, out of which about 60 per cent was retained in passive pools and only 11 per cent in active pools.
- Increasing levels of lantana addition and fertilizer application increased total C stock, C stock ha^{-1} yr^{-1} and retention of all active and passive pools of carbon.
- With improvement in all the pools of N, P and S as well as physical, chemical and biological parameters of the soils with increasing levels of lantana addition and fertilizer application, the maximum rice and wheat yield was obtained under 20 t ha^{-1} lantana addition alongwith 66 per cent of N and K addition indicating, thus, saving of 33 per cent of N and K to rice and N, P and K to wheat.
- Among SOM pools, WS-CHO and SMB-C and among nutrients pools, SMB-P, available-N and WS-OC were the most important pools for rice and wheat production.
- The Roth-C-26.3 model could predict the soil carbon dynamics as it fitted well with the observed data under the present set of nutrient management and environmental conditions.



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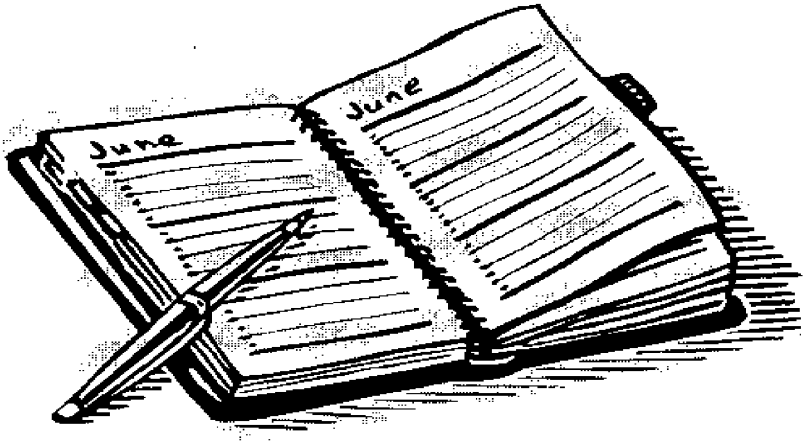

Appendices

Appendix-I

Mean monthly rainfall, air temperature and open pan evaporation for the period 1988-2005

Month	Rainfall (mm)	Temperature (°C)		*(Evap 0.75) mm
		Maximum	Minimum	
January	67.8	15.7	5.2	53.7
February	86.2	16.9	6.7	64.3
March	99.4	20.8	10.0	104.2
April	43.3	26.1	14.8	157.3
May	56.9	30.2	18.4	210.5
June	181.4	30.0	19.6	171.4
July	527.0	26.9	19.8	91.5
August	644.0	26.2	19.5	74.9
September	228.5	26.6	17.6	84.1
October	13.9	25.0	13.7	104.1
November	15.5	21.4	10.1	101.3
December	51.4	17.9	6.7	56.3

*(Evap 0.75) : Open pan evaporation (Muller, 1982)

Appendix-II

Total annual rainfall (mm) of Palampur for the period 1988 to 2005

Year	Rainfall (mm)
1988	2338.6
1989	1893.9
1990	3229.4
1991	2169.1
1992	2524.2
1993	1893.6
1994	2045.1
1995	1826.3
1996	1346.1
1997	1558.2
1998	2021.4
1999	2164.0
2000	1763.0
2001	1572.6
2002	1126.4
2003	2102.5
2004	2200.0
2005	2352.0
Means (18 years)	2007.0

Appendix-III

Long-term effect of Lantana addition and fertilizer application on Humic acid-N (g/100g of soil)

Lantana addition ($t\ ha^{-1}$)	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	0.78	0.86	0.89	0.85
10	0.85	0.88	0.99	0.91
20	1.23	1.24	1.25	1.24
30	1.36	1.39	1.42	1.39
Mean	1.05	1.09	1.14	
LSD = (0.05)	F=NS	L=0.06	FxL=NS	
		(0.15 – 0.30 m)		
0	0.59	0.62	0.66	0.62
10	0.63	0.65	0.69	0.66
20	0.71	0.74	0.77	0.74
30	0.79	0.81	0.84	0.81
Mean	0.68	0.71	0.74	
LSD = (0.05)	F=NS	L=0.03	FxL=NS	

Appendix-IV

Long-term effect of Lantana addition and fertilizer application on Fulvic acid-N (g/100g of soil)

Lantana addition ($t\ ha^{-1}$)	Fertilizer application (% of the RD)			
	33	66	100	Mean
	(0 – 0.15 m)			
0	0.29	0.29	0.30	0.29
10	0.31	0.33	0.35	0.33
20	0.34	0.36	0.39	0.36
30	0.38	0.41	0.44	0.41
Mean	0.33	0.35	0.37	
LSD = (0.05)	F=0.10	L=0.13	FxL=NS	
	(0.15 – 0.30 m)			
0	0.22	0.22	0.24	0.23
10	0.24	0.25	0.25	0.25
20	0.26	0.27	0.28	0.27
30	0.28	0.29	0.30	0.29
Mean	0.25	0.26	0.27	
LSD = (0.05)	F=0.01	L=0.01	FxL=NS	

Appendix-V

Long-term effect of Lantana addition and fertilizer application on Humic acid-S (g/100g of soil)

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
	(0 – 0.15 m)			
0	0.22	0.23	0.23	0.22
10	0.30	0.36	0.41	0.36
20	0.40	0.45	0.51	0.45
30	0.48	0.51	0.57	0.52
Mean	0.35	0.39	0.43	
LSD = (0.05)	F=0.02	L=0.03	FxL=NS	
	(0.15 – 0.30 m)			
0	0.11	0.12	0.13	0.12
10	0.14	0.16	0.17	0.16
20	0.18	0.21	0.23	0.21
30	0.23	0.24	0.26	0.24
Mean	0.17	0.18	0.20	
LSD = (0.05)	F=0.009	L=0.02	FxL=NS	

Appendix-VI

Long-term effect of Lantana addition and fertilizer application on Fulvic acid-S (g/100g of soil)

Lantana addition (t ha^{-1})	Fertilizer application (% of the RD)			
	33	66	100	Mean
		(0 – 0.15 m)		
0	0.12	0.15	0.18	0.15
10	0.17	0.22	0.27	0.22
20	0.22	0.27	0.32	0.27
30	0.27	0.31	0.37	0.32
Mean	0.20	0.24	0.29	
LSD = (0.05)	F=0.01	L=0.02	FxL=NS	
		(0.15 – 0.30 m)		
0	0.08	0.10	0.11	0.10
10	0.11	0.12	0.13	0.12
20	0.14	0.16	0.19	0.16
30	0.17	0.19	0.21	0.19
Mean	0.13	0.14	0.16	
LSD = (0.05)	F=0.01	L=0.01	FxL=NS	

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