

CARBON DYNAMICS IN RICE – WHEAT SYSTEMS

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CARBON DYNAMICS IN RICE – WHEAT SYSTEMS

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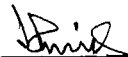
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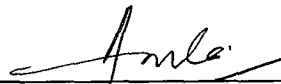
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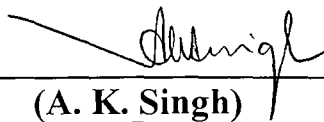
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CERTIFICATE

This is to certify that the thesis entitled '**Carbon Dynamics in Rice-Wheat Systems**' submitted in partial fulfilment of the requirements for the award of the degree of **Doctor of Philosophy in Environmental Sciences**, to the Post-Graduate School, Indian Agricultural Research Institute, New Delhi, is the genuine record of the *bona fide* research carried out by **Miss Bidisha Banerjee**, under my guidance and supervision. No part of the thesis has been submitted for any other degree or diploma.

All the help and assistance received during the course of this investigation has been duly acknowledged.



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Introduction

Carbon (C) is an essential element for life on earth. It exists in several forms and is cycled between several biotic reservoirs, including the oceans, terrestrial biota and atmosphere. Principal global C pools include oceanic (37000 Gt), geologic (50000Gt), soil (1500 Gt), atmospheric (740 Gt), and biotic (550 Gt) components (Lal, 2001). Carbon cycle holds centre stage in global change studies due to its role in influencing weather and determining food, fibre and wood supply for human use through plant productivity.

Over the past few decades, the man-induced changes in the climate of the earth have become the focus of scientific and social attention. The most imminent of the climatic change of the earth is the increase in the atmospheric temperatures due to the increased levels of carbon dioxide (CO₂) and other greenhouse gases. The CO₂, methane and nitrous oxide concentrations were 280 ± 6 ppm, 700 ± 60 ppb and 270 ± 10 ppb between 1000 and 1750 AD. Today, these values have become 369 ppm, 1750 ppb and 316 ppb, respectively (IPCC, 2001). Carbon dioxide (CO₂), the principal greenhouse gas, currently accounts for about 60% of the net radiative forcing and has a strong potential to affect current and future climate. The quantity of rainfall and its events has also become more uncertain. In certain places, climatic extremes such as droughts, floods, timing of rainfall and snowmelt have also increased. The sea level has risen by 10-20 cm with

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regional variations. Similarly, snow cover is also believed to be gradually decreasing. The global mean annual temperatures at the end of the 20th century are almost 0.7 °C above those recorded at the end of the 19th century. The 1990s were, on an average, the warmest decade of the earth since instrumental measurement of temperature started in 1860's and the 1900s the warmest century during the last 1000 years. The seven warmest years recorded globally have occurred in the last decade. All these changes have been ascribed primarily to the combustion of fossil fuel and land use changes. The Inter-Governmental Panel on Climatic Change (IPCC) of the United Nations in its recent report has again confirmed the global warming trend and projected that the globally averaged temperature of the air above the earth's surface would rise by 1.4-5.8 degrees Celsius over the next 100 years (IPCC, 2001).

IPCC has recently compiled the projected magnitude of future change in temperature, rainfall and carbon dioxide for different parts of the world (Watson et. al., 1998). According to this, by 2100, CO₂ level will increase to 397 - 416 ppm from the current (2000) level of approximately 370 ppm. This will further increase to 605 - 755 ppm by 2070. There is considerable uncertainty in the magnitude of change in rainfall and temperature as well predicted for India (Table 1). Relatively, the increase in temperature is projected to be less in kharif

than in rabi. The rabi rainfall will, however, have larger uncertainty. Kharif rainfall is likely to increase by as much as 10%.

Table 1. The expected magnitude of change in climatic factors in south Asia by 2010 and 2070 AD due to global warming (Watson et. al., 1996).

Climatic factors	Rabi		Kharif	
	2010	2070	2010	2070
Temperature increase, °C	0.3 to 0.7	1.1 to 4.5	0.1 to 0.3	0.4 to 2.0
CO ₂ , ppm	397 to 416	605 to 755	397 to 416	605 to 755
Rainfall change in southwest monsoon region, %	0	-10 to +10	0	0 to +10

Such global climatic changes will affect agriculture through their direct and indirect effects on crops, soils, livestock and pests. Increase in atmospheric carbon dioxide has a fertilization effect on crops with C3 photosynthetic pathway and thus promotes their growth and productivity. Increase in temperature, depending upon the current ambient temperature, on the other hand, can reduce crop duration, increase crop respiration rates, alter photosynthate partitioning to economic products, effect the survival and distributions of pest populations thus developing new equilibrium between crops and pests, hasten nutrient

mineralisation in soils, decrease fertiliser use efficiencies, and increase evapotranspiration. Indirectly, there may be considerable effects on land use due to snow melt, availability of irrigation, frequency and intensity of inter- and intra-seasonal droughts and floods, and availability of energy. All of these can have tremendous impact on agricultural production and hence food security of any region.

The increasing level of CO₂ in the atmosphere, the most important greenhouse gas, is mostly because of fossil fuel combustion. Similarly, the industrial processes and products only cause Chlorofluoro carbon (CFC) emissions. The increased agricultural activities and organic waste management are presumed to be contributing to the build-up of methane and nitrous oxide in the atmosphere. The total annual injection of methane into the atmosphere from all sources in the world is estimated to be 535 Tg yr⁻¹. Although the increase in annual load of methane in the atmosphere is much less than that of CO₂, its high impaired absorption amounts to higher contribution (15-20%) in the global warming.

Large emissions of methane from paddy fields and livestock have been ascribed to India based on the studies carried out in North America. According to a US-EPA estimate in early nineties based on extrapolation of measurements in USA and Europe, the annual emissions from Indian rice paddies were 37.8 Tg CH₄. Several initiatives were taken in ICAR and in CSIR institutes and

systematic measurements of emissions were made from various sources (Sinha, 1995; Parashar et al., 1994). These measurements showed that the US estimates were very biased and Indian rice fields contribute only 3.6 Tg methane per annum. The main reason of low methane emission from rice fields in India is that the soils of major portion of rice growing areas have very low organic carbon and not all paddies are continuously flooded. Methods for reducing even these small GHG releases from rice paddies have been identified but need refinement for developing them as technologies. Mid-season drainage from flooded fields and application of single super phosphate with high sulphate have mitigation potential. Many of the mitigation options are, however, location-specific effects as they depend on soil types, cultivars, and cultural practices. Intensive research on these options is being conducted before advocating them as technologies for mitigating greenhouse gas emissions from rice soils. It was also estimated that the enteric fermentation in livestock also contributes 7.6 Tg methane.

Although agriculture is not a large emitter of green house gases (GHGs), it can assist in reducing the overall carbon emissions by sequestering this in large area of land. Following the agreement of the Kyoto protocol in 1997 efforts are being made by various agencies to examine sinks of carbon in different areas. The key parameters in assessment of mitigation strategies are: the amount of carbon per unit of land that can be conserved or sequestered in vegetation and soil by a given

management option, the time period over which this can be conserved or sequestered, the amount of available land, for this purpose and the mitigation costs. These parameters vary by land use type, soil type, environmental and socio-economic factors, which in turn also vary by region.

Several studies have been initiated in Indian National Agricultural Research System to determine the effect of various agricultural management strategies such as zero tillage, mulching, incorporation of green manure, silvi-pastoral systems and watershed management on enrichment of soil carbon. The prominent role of forestry & agroforestry systems in carbon sequestration has also increased global interest in these land use options to stabilize green house gas emission. Agroforestry system especially agri-silvicultural system can be carbon sinks and temporarily store carbon. In one of the studies in Uttar Pradesh, approximately 20 million tons of carbon has been estimated to be sequestered by the farm forestry plantations. The carbon sequestration potential of agroforestry practices is however quite variable, depending on choice of trees and associated crops, the planting density and production objective of the system.

Agricultural soils represent a potential sinks for carbon although they also serve as a source through soil respiration. Cultivation practices such as tillage can also enhance soil aeration, mineralization of soil organic carbon (SOC) and the flux of CO₂ from soils. Indian soils are largely carbon-depleted but can be brought back

to their native carbon- carrying capacity by reforestation. The current stock of organic carbon in Indian soils (24.3 Gt) can be increased to 34.9 Gt, the difference representing the potential for sequestering additional carbon in soils. The soil constitutes a significant reservoir of carbon in both mineral and organic forms. The carbon in the soil has a special feature through humus formation. Soil carbon is an important part of the terrestrial carbon pool. The soil organic carbon pool is about 2.1 times that of the atmospheric pool and about 2.7 times that of the biotic pool comprising land plants. Humus is considered as the most important fraction of soil organic matter. Enhanced sequestration of atmospheric CO₂ in the soil, ultimately as stable humus, may well prove a more lasting solution than temporarily sequestering CO₂ in the standing biomass through reforestation and afforestation. Such actions will also help to reverse processes of land degradation, thus contributing to sustained food productivity and security for the people in the regions concerned. Thus, important and strategic objectives of selecting soil management options are to decrease the efflux of CO₂ from soil to the atmosphere, and increase the total soil organic carbon pool at the expense of the atmospheric carbon pool.

Predominant pedospheric processes that affect soil organic carbon dynamics may be grouped into two categories:

SOC enhancing processes (plant biomass production, humification, aggregation and sediment deposition).

SOC degrading processes (soil erosion, leaching and SOC decomposition).

The SOC content is generally high in virgin soils under grass and forest vegetation. Conversion of grass and forestland to cropland and pastures leads to losses of SOC. Changes in SOC content is the net result of carbon input and carbon loss. Increase in carbon storage can be achieved by adopting a new management practice which includes (a) increase the amount of carbon entering the soil (b) suppress the rate of soil carbon decomposition. Scientists of the Intergovernmental Panel on Climate Change (IPCC) have calculated that over the course of the next 50 to 100 years between 40 and 80 Gt C might be absorbed in agricultural soils by applying tried-and-true land management practice. Although cultivation too often in the past has been associated with organic matter loss and soil degradation, we are now in a position to apply our understanding of crop sequences and cultivations in a way that can actively restore organic matter storage thereby restoring the functions that the soil supports. This is important both at the global scale, enabling projection of carbon mitigation potentials in agriculture, and at the regional scale, enabling an optimum organic carbon level to be specified.

Indo-Gangetic plain (IGP) within South Asia, spread across Pakistan, India (northwest and northeast), Nepal and Bangladesh and characterized by fertile soils, favourable climate and abundant surface and groundwater, is the backbone of food security for the countries of the region. Rice and wheat, the major cereal crops of this region grown in rotation in almost 12 million hectares are the principal source of food, nutrition and livelihood security for several hundred millions of people in this densely populated region (Paroda et al., 1994). Rice-wheat systems cover about 32% of total rice area and 42% of total wheat area in these four countries and account for one-quarter to one-third of total rice and wheat production (Ladha *et al.* 2000).

In the IGP, the increased adoption of rice-wheat during last three decades has resulted in a heavy usage of irrigation, fertilizer, electricity and diesel. These have a direct impact on the emissions of the greenhouse gases viz., CO₂, CH₄ and N₂O. It has been estimated that on an annual basis, rice-wheat system in IGP emits GHGs which has a global warming potential of 3000 to 8000 kg ha⁻¹ of carbon depending upon the management practices used (Grace et al., 2003). Multiplying this figure with the total area under intensive cultivation suggests considerably large emissions of GHGs from IGP, an issue of global concern. Increasing production in future through intensification may further increase the emissions of GHGs.

Recent researches have shown that surface seeding or zero-tillage establishment of upland crops after rice gives similar yields to when planted under normal conventional tillage over a diverse set of soil conditions. This reduces costs of production, allows earlier planting and thus higher yields, results in less weed growth, reduces the use of natural resources such as fuel and steel for tractor parts, and shows improvements in efficiency of water and fertilizers. In addition, such resource conserving technologies restrict release of soil carbon thus mitigating increase of CO₂ in the atmosphere. It is estimated that zero tillage saves 29.9 litres of diesel as compared to the conventional tillage. This leads to 77.7 kg ha⁻¹ year⁻¹ reduction in CO₂ production (assuming 2.6 kg CO₂ production per litre of diesel burnt).

In view of its importance, several studies have earlier focused on studying the carbon dynamics in rice-wheat systems (Ladha et al., 2003). Most studies have focused on quantifying the above ground carbon dynamics in terms of yield trends from the system and in understanding the principal causes of the trends. Long-term experiments conducted in Indian IGP showed that there is a stagnating or declining trend in productivity at several locations even with application of N, P, and K fertilizers under modern intensive farming (Nambiar and Abrol 1989, Sinha et al., 1998). Over time we have been removing more nutrients than the amount externally added through fertilisers. Farmers, therefore, have to apply

more fertilisers to get the yield as they were getting with less fertiliser 20-30 years ago.

Although there are reports indicating declining organic carbon in these systems (Swarup, 1998) much work needs to be done to clearly understand the soil carbon dynamics. We need to identify such carbon management strategies that may anyway be needed for sustainable development of agriculture. Enhancing organic matter content of our soils will, for example, ensure better soil fertility as well as assist in sequestering atmospheric carbon. Enhanced soil carbon could possibly also at a later date be used for carbon trading to sell these credits to carbon deficit nations. This, would, however, require long-term assessment of the effects of different land use management strategies on food production as well as soil organic carbon in different regions. Conventional field experiments in critical regions are best suited but can be very time consuming for assessing the long-term effects. Dynamic simulation models of crop growth can be used to supplement field research and to determine the long-term consequences of agricultural management on carbon dynamics. These models are holistic, knowledge based tools that are generic in nature and have been applied for local and global applications. They are based on quantitative understanding of underlying process, and integrate the effect of soil, weather, crop, pest and management factors on growth and yield. These explanatory models are

quantitative description of the mechanisms and processes that result in growth of the crop. The processes could be crop physiological, meteorological, soil physical or chemical. Crop simulation models have been useful for integrating knowledge from different disciplines. Since these are process based, they can be used at any place, irrespective of the location where developed. These models have the added advantage that they can be tested via field experiments. Together with other tools of systems approaches such as expert systems, decision support systems, databases, GIS and remote sensing, they constitute a valuable tool of information technology that can greatly facilitate integration of knowledge and its transfer to a variety of users.

These approaches have been used in recent past for determining the production potential of a location knowing its resources, germplasm and the level of available technology, in matching agro-technology with the farmers resources and in analysing the precise reasons for yield gap, in estimating crop yield before the actual harvest, in studying short- and long- term consequences of agricultural practices on agricultural environment including carbon dynamics, and to study the consequences of climatic variability and climatic change on agriculture . This study, therefore, employs field experiments, historical databases, as well as simulation models to understand the carbon dynamics in the rice-wheat systems of the Indo-Gangetic plains. The specific objectives of the study are:

1. To study carbon dynamics in rice-wheat cropping system in field.
2. To test a model for studying carbon dynamics in rice-wheat cropping system.
3. To extrapolate the results of rice-wheat system to other sites in the Indo-Gangetic plains.

Since above ground dynamics has been studied earlier by several researchers, greater emphasis in the field experiments has been put on the soil carbon dynamics.

Review of literature

Soil Carbon dynamics

Soil carbon (C) dynamics is important in maintaining crop productivity and delicate balance of atmospheric carbon dioxide (CO₂) since 75% of the terrestrial C is held by soils. The quantity of carbon stored in soils is nearly three times higher than that in the above ground biomass and approximately twice as high as in the atmosphere (Eswaran *et al.*, 1993). The amount of carbon stored in agricultural soils is approximately 170 Gt C (Paustian *et al.*, 2000) while vegetation contains 550 Gt C. The carbon stocks of Indian soils have been calculated using organic carbon data of soil profiles from various sites (Gupta and Rao, 1994). The current total stocks are estimated to be 24.3 Gt of carbon, which is 1.6-1.8% of the carbon stored in the world's soils. The carbonate and non-carbonate rocks have the largest store of carbon (78800 Gt) and the fossil fuels (coal, lignite and hydrocarbons) have a carbon pool of 117 Gt (Dadhwal and Nayak, 1993).

The primary source of the C is through biomass produced and its incorporation into the soil. The principal loss of C is through respiration, decomposition, erosion and leaching. Land use and management affect both the magnitude of production and rate of removal of soil organic carbon (SOC). Though tropical conditions favour organic matter decline due to higher rate of mineralization, its

levels seldom reach a stage of complete exhaustion. Rather, over cultivated soils tend to attain a steady state, described as a lower equilibrium limit by Buyanovsky and Wagner (1998). In general, organic matter content of tropical soils can fall to as low as about 30%, but most commonly to about 60% of that found under indigenous vegetation, within an average of 10 years of arable farming (Brown *et al.*, 1994).

Worldwide it is estimated that conversion of land to agricultural uses resulted in the loss of 50-100 billion tonnes of C from soils, over the past 200 years (Lal, 2001). Even today, conversion of forests to agriculture in the tropics continues to be an important source of CO₂ emissions, from biomass and soils to the atmosphere. Most soils loose one third to half of their native SOC pool upon conversion from natural to agricultural ecosystems (Donigian *et al.*, 1998; Singer and O' Quinn, 1999). The SOC loss is accentuated when inputs of organic C in cultivated systems are lower, and losses due to mineralization and erosion are higher than in natural systems. The cumulative historic loss of C due to cultivation since the dawn of settled agriculture has been varyingly estimated at 40 Gt (Houghton, 1995), 55 Gt (IPCC, 1995), 66-90 Gt (Lal, 1999a), 150 Gt (Bohn, 1978), 500 Gt (Wallace, 1994), and 537 Gt (Buringh, 1984).

The role of agro ecosystem in total C cycle in India is significant since approximately half of the total land area (329 M ha) is arable land (166 M ha)

(Dadhwal and Chhabra, 2000). Soil C pools and fluxes in agro ecosystems are influenced by a number of factors including C inputs (e.g. amount and type of plant residue), climatic (e.g. temperature, precipitation) and edaphic (e.g. soil texture, pH, drainage) conditions (Cole *et al.*, 1993). In addition, land use and management strongly influence C in agricultural soil which complicates our understanding of its role in the global C cycle.

Fractions of soil carbon

Carbon pools in soil occurs in two forms, soil organic carbon (SOC) and soil inorganic carbon (SIC). SOC pool includes highly active humus and relatively inert charcoal C while SIC includes elemental C and carbonate minerals such as calcite, dolomite and gypsum (Lal, 2001). The soil organic matter comprises the sum of all organic substances in soil. It consists of a mixture of plant and animal residues at various stages of decomposition of substances synthesized microbiologically or chemically from the breakdown products and of the bodies of live microorganisms and small animals and their decomposition products (Schnitzer, 1991). Studies of SOM have yielded some clearly different fractions based on particle size or density (Tiessen *et al.*, 1984; Hassink, 1994). Coarse, light material ($>50\text{ }\mu\text{m}$) is composed of recent litter that is still actively being transformed and whose nutrients are readily available. Fine clay sized material ($<0.2\text{ }\mu\text{m}$) contains organic matter of recent microbial origin whose associated

nutrients are easily available. These fractions affect nutrient cycling and availability in the short term, and are highly responsive to land use changes and management. Intermediate size fractions, contain stabilized SOM, which contains nutrients of low availability. Saussure (1804) is usually credited with introducing the term “humus” to describe the dark coloured organic material in soil. During the period 1900-1940 renewed efforts were made to classify humic substances and to determine their chemical nature and structure. Oden (1919) classified humic substances into the following groups: humus coal, humic acid, hymatomelanic acid and fulvic acid. Waksman (1936) regarded humus as a mixture of plant derived materials, including fats, waxes, resins, hemi cellulose, cellulose and lignoprotein. Humus or soil organic matter is now known to include a broad spectrum of organic constituents, many of which have their counterparts in biological tissues (Stevenson, 1982). Thus two major types of compounds can be distinguished, (1) non humic substances, consisting of compounds belonging to the well known classes of organic chemistry and (2) humic substances, a series of high molecular weight brown to black substances formed by secondary synthesis reactions. Included in the first group are such constituents as amino acids, carbohydrates and lipids. Compounds in the second group are distinctive to the soil or sediment environment. Several studies identified specific fractions of organic matter that describe soil quality (Rees *et*

al., 2001). These include macroorganic matter, microbial biomass and carbohydrate contents. Silt and sand sized macroorganic matter is important in maintaining the protection effect of SOM. All the fractions and sub fractions of humus represent a group of polymers linked together by a chain of interconversions.

Factors affecting SOC dynamics

Studies have shown that soil organic carbon dynamics is influenced by several factors such as soil texture, temperature, moisture, pH, and available C and N.

Temperature

Temperature has great influence on organic carbon depletion from soil. According to Syers *et al.* (1996) prevalence of warm temperature in the tropics accelerates organic matter decomposition and loss. At low temperatures ($> 0^{\circ}\text{C}$) plant growth is greater than the rate of microbial decomposition and organic matter can accumulate. Above 25°C microbial decomposition is greater than plant growth hence organic matter production declines. In a study maximum carbon dioxide production rate was noted in mid July ($19 \text{ g m}^{-2} \text{ d}^{-1}$), which is attributed to the increasing role of soil respiration, root activity and organic matter decomposition with the increase in temperature (Buyanovsky *et al.*, 1986). Tropical Indian soils, majority of which belong to arid and semiarid climate, rarely exhibit organic carbon levels exceeding 0.6% (Virmani *et al.*,

1982). Their counterparts in temperate environments have organic carbon levels ranging between 1.2% to 2.5% (Dudal, 1965).

Moisture

Besides temperature, soil moisture content also affects organic carbon content of soil. These two factors are interdependent with the influence of soil water-content being stronger at higher temperatures. Organic matter distribution across soils is influenced strongly by mean annual rainfall (Katyal *et al.*, 2000). Increasing soil moisture content results in increasing carbon dioxide evolution when the soil water - content is suboptimal for microbial activity. Periodic drying and wetting of the soil also increases CO₂ evolution (Birch, 1955).

Soil texture

Soils in their natural or undisturbed state contain large SOC pool, the size of which depends on soil texture (Lal, 2001). Soil texture affects water infiltration and gas diffusion and thereby organic matter decomposition and hence CO₂ formation and emission. Soils with high clay content generally have higher organic matter content, due to slower decomposition of organic matter.

Soil pH

Soil pH has a profound effect on soil organic matter preservation and decomposition; although its precise mode of influence has yet to be fully established (Motavalli *et al.*, 1995). It strongly influences the growth of bacteria,

fungi and soil fauna. Microbial activity at very low or very high soil pH will influence the rate of organic matter decomposition. In soils having pH 3.0, 2- to 12-fold less CO₂ concentration has been observed than at pH 4.0 (Sitaula *et al.*, 1995) due to the adverse effect of low pH on soil microbial activity, which lowers organic matter decomposition. Rao and Pathak (1996) reported that at pH 8.7, CO₂ emission was found to be reduced by 18% and at pH 10.0 by 83% compared to that at pH 7.0.

Salinity

Excessive amount of salts have adverse effect on physical and chemical properties of soil as well as on soil microbiological processes. A progressive decrease in CO₂ evolution occurs with increase in salinity. It was observed that carbon mineralization is similar in soils up to the electrical conductivity (EC) value 26 d S m⁻¹, but gets drastically reduced at higher EC (Pathak and Rao, 1998).

Atmospheric pressure

CO₂ emission is directly related to atmospheric pressure. Its decrease triggers the release of CO₂ from the soil, thereby enhancing CO₂ emission. Baldocchi and Meyers (1991) noted that low atmospheric pressure increased CO₂ emission from a deciduous forest soil.

Organic manure

Soil organic carbon levels were either maintained or increased with an adequate manure treatment (Katyal, 2000). Application of organic matter minimizes erosion mediated organic matter loss. However, climatic conditions in the dry tropics favour its disappearance as CO₂. The soluble organic carbon in soil is an immediate source of carbon for soil microorganisms, which in turn emit CO₂ (McGill *et al.*, 1981). Manures including sewage sludge increase the soil respiration by a factor of 2-3 (Scott *et al.*, 2000). Alvarez *et al.*, (1999) found that increase of CO₂ emission from the soil represented 21% of C applied through sludge. Incorporation of straw in soil increased CO₂ flux from 0.3 to 1.3 kg CO₂ ha⁻¹ d⁻¹ (Curtin *et al.*, 1998). Crop residues, with high N content (grain legumes or fodders), can accelerate the decomposition of soil organic matter because of the availability of additional N to the microbial population.

Fertilizer application

Fertilizers generally increase soil organic carbon content because the increased crop growth returns larger amounts of residues to the soil. Aerts and Toet (1997) suggested that increase in the supply of NH₄⁺N leads to reduction in the decay of organic matter and loss of C. However, application of nitrogenous fertilizer affects CO₂ emission directly by providing N to microbes, which, in turn, increase the decomposition of soil organic matter (Katznelson and Stevenson,

1956). In tropical soils application of fertilizers at suboptimal rates cause reduction in the SOC pool.

Use of nitrification inhibitors

Nitrification inhibitors, viz. DCD (dicyandiamide), nitrapyrin, sodium thiosulphate, 2-amino-4-chloro-6-methyl-peyremidine (AM), and acetylene inhibit the nitrification process (Prasad and Power, 1995). These chemicals are recommended to increase nitrogen-use efficiency and reduce N-loss through leaching and denitrification. However, these chemicals also act on those microbes, which are engaged in the oxidation of organic carbon and reduce CO₂ emission. It has been shown that a nitrification inhibitor, encapsulated calcium carbide (a slow release source of acetylene), reduces carbon dioxide emission and appears to be effective in minimizing emission of this greenhouse gas in flooded rice (Bronson and Mosier, 1991).

Vegetation

Another important factor influencing organic carbon levels in soil is the nature and amount of vegetation. The presence of crops also influences carbon dynamics in soil. The production of carbon dioxide is approximately 2 to 3 fold more in cropped soils compared to bare soils (Russell, 1973). Within different crops also, there is variability in carbon dioxide production. In an alluvial, sandy loam soil, having pH 7.5 and organic matter 0.66%, planted to wheat and maize

crops, CO₂ emissions have been found as 36.7 and 61.7 kg CO₂ ha⁻¹ d⁻¹, respectively.

Tillage

Ploughing causes rapid, large changes in decomposition, exposing SOM previously protected inside soil aggregates (Tiessen *et al.*, 1994). During a tillage event, soil aggregates are broken, increasing oxygen supply and surface area exposure of organic material. This promotes the decomposition of organic matter. Thus, more CO₂ emission can occur from a tilled than from an undisturbed soil (Doran, 1980). In contrast conservation tillage favoured organic carbon enrichment of soils (Lal, 1999). Dao (1998) observed that the proportion of soil organic C respired in the 60 day period was twice as great under mould board ploughing than under no tillage.

Methane emission from soil

Paddy fields are important sources of methane. Methane emission from rice fields was noted by Harrison and Aiyer as early as 1913, however, the first *in situ* measurement of the methane flux was done in California, USA in late 1970s (Cicerone and Shetter, 1981), followed by the extensive studies in several countries of the world (Aulakh *et al.*, 2001). These field experiments stressed the importance of rice plant as a pipe for methane transport from soil to the atmosphere. At present, the methane source strength of wetland rice fields is

estimated to be 60 Tg yr^{-1} , with a range of $20 - 100 \text{ Tg yr}^{-1}$ (IPCC, 1996). The biological formation of methane (methanogenesis), is a geochemically important process that occurs in all anaerobic environments where organic matter undergoes decomposition. The biogenic methane results from the metabolic activities of a bacterial group that are the terminal members of the food chain in their ecosystem and are called methanogens. Methane is produced by the reduction of soil organic carbon under anaerobic conditions having redox potential less than -150 mV (Wang *et al.*, 1993).

Factors regulating methane emission

Methane production in soil is affected by the prevalent weather conditions, water regime, soil properties and various cultural practices like irrigation and drainage, organic amendments, fertilization and rice cultivars.

Temperature

Temperature plays an important role in the activity of soil microorganisms, and hence affects methane production. Most of the methanogenic bacteria display optimum rates of methane production at around $30^{\circ}\text{--}35^{\circ}\text{C}$ with very little methanogenesis between 5°C and 15°C (Yagi *et al.*, 1997). The methane emission rate increases sharply when the soil temperature rises from 20 to 25°C , corresponding with a temperature coefficient (Q_{10}) of about 4 (Holzapfel-Pschorn and Seiler, 1986).

Methanogenesis is a highly pH-sensitive process and a small change in the pH value sharply lowers the methane production. Most of the methanogens are neutrophilic, hence methane production is most efficient in the pH range 6.4 - 7.8. Below pH 5.8 and above 8.8, methane production is almost completely inhibited.

Redox potential (Eh)

Methanogenesis occurs only under anaerobic conditions. A sufficiently low value (-150 mV) of redox potential (*Eh*) is required for methane production and it is negatively related to methane emission. Flooded rice soils may have *Eh* values as low as -250 to -300 mV, while *Eh* of -150 to -190 mV is needed for methane formation (Wang *et al.*, 1993). However, there are reports that CH₄ production in freshly flooded rice soils is initiated much earlier than generally expected in spite of high *Eh* values. This early initiation of methane production is due to the presence of enough viable methanogenic archaea in the soils (Roy *et al.*, 1997).

Organic amendments

Methanogenesis process is enhanced by the application of organic manure and crop residues. The amount of methane formed in paddy soils is positively correlated with soil organic-carbon and water-soluble organic-carbon.

Incorporation of rice straw in soil increases methane production by 120–800% over that of unamended soil. The method of incorporation of straw is also important in regulating methane emission. Methane emission is highest with the incorporation of straw followed by straw compost, zero tillage with straw mulching and least with straw ash application (Chaareonsi *et al.*, 2000). Application of biogas spent slurry as a manure results in lowering of methane emission compared to application of farmyard manure (FYM) from rice fields (Debnath *et al.*, 1996).

It has been found that growing of azolla for biological nitrogen fixation could enhance methane emission from rice fields due to mediation of methane transport from floodwater of rice soil into the atmosphere (Ying *et al.*, 2000). The presence of azolla could modify the chemical properties of soil, stimulating methane production and decreasing the *in situ* methane removal. It also lowers the *Eh* value, which increases the methane production.

Cultivars

Plant influences the methane efflux by (i) providing channels (aerenchyma) for the transport of methane from soil to the atmosphere, (ii) releasing root exudates or root autolysis products to methanogenic bacteria, and (iii) creating oxic environment in the anoxic soil through the transport of O₂ into the rhizosphere stimulating the oxidation of methane and inhibiting methanogenesis (Wassmann

et al., 2000). There are significant variations in the quantities of methane emitted from soils growing different cultivars. Early-maturing cultivars emit less methane compared to that from late-maturing cultivars. The high yielding varieties like IR-64 show moderately high emission (Setyanto *et al.*, 2000).

Mineral fertilizers

Methane fluxes are strongly influenced by the type, method and the rate of fertilizer application. Sulphate-containing fertilizers reduce methane emission. It has been observed that methane emission, on an average, decreased by 42 and 60% in the ammonium sulphate treatments and 7 and 14% in the urea treatments at rates of 100 and 300 kg N ha⁻¹, respectively, compared to control (Cai *et al.*, 1997). Phosphogypsum, a sulfate-containing by-product of industrial production of phosphoric acid, reduces methane emission by 56-73% when applied in combination with urea (Sethunathan *et al.*, 2000). In a field study P applied as single super phosphate (SSP) inhibit methane emission from a flooded field plot planted under rice (Adhya *et al.*, 1998).

Water management

Soil water regime is an important factor for the gas exchange between soil and atmosphere and has a direct impact on the processes involved in methane emission. Drainage is a major modifier of seasonal methane emission pattern. A single mid-season drainage may reduce seasonal methane emission. This

emission could be reduced further by intermittent irrigation yielding a 30% reduction as compared to mid-season drainage (Lu *et al.*, 2000). In a four-year study in northern India it has been observed that low emissions are indirectly caused by high percolation rates of the soil and the frequent water replenishments cause constant inflow of oxygen in the soil (Jain *et al.*, 2000).

Salts

Methane emission is inversely related to salinity and sulphate concentration in soil. The sulphate and sulphides may be toxic to methanogens and hence reduce methane production. Between the two main pathways of methane formation, the reduction of CO₂ is less susceptible to salt (NaCl) than the decomposition of acetic acid (Saenjan and Wada, 1990).

Soil texture

Soil texture and mineralogy, through their effect on puddling can affect percolation rate of water and thereby net emission of methane in waterlogged paddy soils. Clay soils form cracks on drying and thus facilitate the release of entrapped methane into the atmosphere.

Methane emission studies in India

There has been lot of research to estimate methane emissions from Indian agriculture. For example, Indian Agricultural Research Institute has been engaged in research on greenhouse gas emissions from agriculture since 1993 to understand the

soil, plant and greenhouse gas emission mechanism in detail and to reduce the uncertainties in the greenhouse gas emission estimates and mitigate the emissions. The institute has standardized the techniques of gas emission measurement, conducted several field experiments to measure the emissions of methane and nitrous oxide from agricultural soils, developed the inventory of methane and nitrous oxide emission and evaluated various strategies to mitigate the emission. It has been observed that the continuously saturated soil in paddy fields gave higher CH_4 emission compared to intermittent wetting and drying soil conditions (Jain et al., 2000). Substituting 50% of inorganic N with FYM increased emission by 172% compared to application of entire amount of N through urea (Pathak et al., 2003; Bhatia et al., 2003). Emission of CH_4 from the rice–wheat systems ranged from 16.2 kg ha^{-1} in the unfertilized treatment to 36.5 kg ha^{-1} in urea plus FYM treatment with an average emission of $20.8 \text{ kg CH}_4 \text{ ha}^{-1}$ (Pathak et al., 2003). In wheat negative fluxes of CH_4 ranging from 0.01 to 0.13 kg ha^{-1} were recorded. In the most common fertilizer practice in Indo-Gangetic plains the emission of CH_4 is 21.2 kg ha^{-1} (Pathak et al., 2003). Emission of CH_4 was lowest (28.4 kg ha^{-1}) in the control treatment (no fertilizer) and highest (41.3 kg ha^{-1}) with application of 100% N through organic sources, which serves as source of electrons resulting in higher CH_4 formation (Bhatia et al., 2003). In other studies rice cultivars show pronounced variations in methane emission (Singh et al., 1997; Mitra et al., 1999). It was

observed that nitrification inhibitors like DCD reduced methane emission Malla *et al.*, 2003). Total N content, texture and cation exchange capacity of soil significantly affect methane emission (Mitra *et al.*, 2002).

Modelling soil organic carbon

Soil organic carbon modelling provides a valuable opportunity to explore ways of managing the terrestrial C cycle. Models for the turnover of soil organic matter (SOM) are currently being used: (1) to better understand SOM turnover processes (Jenkinson and Coleman, 1994; Smith *et al.*, 1998b; Falloon *et al.*, 1998a), (2) as part of systems to predict agronomic yields and make recommendations for applications of fertilizer [EPIC (Williams and Renard, 1985); DSSAT (Hoogenboom *et al.*, 1994); SUNDIAL (Smith *et al.*, 1995); and (3) to aid policy decisions regarding C sequestration options, and to investigate the effects of climate change and land use on SOM (Jenkinson *et al.*, 1991; Lee *et al.*, 1993; King *et al.*, 1997; Falloon *et al.*, 1998). The use of these models range from the field level to regional and global applications. Modelling at the regional scale is important for climate change issues. These models can be broadly classified as: (1) a single homogeneous compartment, (2) two compartment, and (3) multi compartmental (Jenkinson, 1990). Models in categories 1 and 2 are mostly static, whereas the models in categories 3 and 4 are

mostly dynamic. The dynamic models can be further split into organism oriented and process oriented models (Paustian, 1994; Smith *et al.*, 1998).

A classic example of an early model dealing with an aspect of C cycling is the potential mineralization work of Stanford and Smith (1972). Other examples include work by Jenny (1941), Henin and Dupuis (1945), and Olson (1963). Dutt *et al.*, (1972) first developed an integrated soil system model containing C and N cycling. In the 1980s, interest in agricultural modeling surged due to the environmental movement, and a range of soil C and N submodels were developed in conjunction with crop and soil focused models such as NCSOIL (Molina *et al.*, 1983), EPIC (Williams and Renard., 1985) and CERES (Ritchie *et al.*, 1986). In the 1990s, several additional models were developed such as DAISY (Hansen *et al.*, 1990), CANDY (Franko, 1996), CENTURY (Parton *et al.*, 1993) and SOIL N (Eckersten *et al.*, 1996).

These models have been difficult to parameterize due to the multiple C pools. Most models differentiate between the various C pools based on their physical, chemical and biological characteristics. Pool sizes and associated rate parameters are difficult to measure and require some model pre runs for self parameterization and initialization (Ma *et al.*, 1998). Understanding the size and age of the different conceptual pools of SOM is of great importance in understanding the global C cycle, for example when estimating how much C is

gained or lost annually from the atmosphere as a result of large-scale land-use change. The different turnover and decomposition rates of soil fractions have been observed by comparison of soils from chronosequences cultivated for different lengths of time (Tiessen *et al.*, 1984). These observations have been integrated into models in order to provide a framework of understanding for processes observed in the field (Parton *et al.*, 1988). Rate coefficients are difficult to determine which may be first order, zero order, Michaelis-Menten kinetics or Monod kinetics (Hansen *et al.*, 1995). First order kinetics remains the most commonly used approach to quantify reaction rates for many of the C processes in soils (Ma and Shaffer, 2001). Rate coefficients are usually modified by environmental factors. The associated rate constants can be derived from literature or calibrated from available data sets (Shaffer *et al.*, 2000).

RZWQM (Ma *et al.*, 1998) has a total of five organic C and N pools, the two surface residue pools and three soil organic matter pools. First order decay rate kinetics is used for all the pools, but with different rate coefficients. It is a fully functional system model and has process level simulations of soil water, soil temperature, plant growth, pesticide fate and C and N dynamics of soil (Ahuja *et al.*, 2000).

CENTURY (Parton *et al.*, 1993) is a model of terrestrial C, N, P and S dynamics and uses a four pool SOM submodel. The pools are, (1) Active pool (soil

microbes and microbial products) with turnover time of 1 to 5 years, (2) Slow pool (resistant plant material and soil stabilized microbial products) with turnover time of 20 to 40 years, (3) Passive pool (physically and chemically stabilized SOM) having 200 to 1500 years turnover time and (4) Structural litter pool (residue) with 1 to 5 years turnover time. It works with a monthly duration time step and simulates SOM to a depth of 20 cm. A potential monthly biomass growth is estimated from temperature, moisture, and plant shading factors, which may be reduced if there is insufficient N, P, and S. The newer version of CENTURY, DAYCENT, has more detailed processes (Del Grosso *et al.*, 2001; Parton *et al.*, 1996).

CENTURY is the most widely tested SOM models, with generally good agreement between observed data and simulated results (Smith *et al.*, 1997). Liang *et al.* (1996) tested the applicability of CENTURY model to soils to examine the relative sensitivity of the model outcome to changes in various parameters. Model results indicated that increased potential crop productivity and reduced harvest index would increase soil organic matter levels under continuous corn in eastern Canada. The model successfully simulates SOM dynamics across climates, land use types and treatments (Kelly *et al.*, 1997). Soil organic C values output from the CENTURY model for a 250 year period demonstrate rising soil organic matter levels from 6000 g m⁻² to final values of 14,880 g m⁻² (organic

matter addition 500 g m^{-2}), and $12,760 \text{ g m}^{-2}$ (organic matter addition 400 g m^{-2}), approaching equilibrium after 150 years (Adderley *et al.*, 2001).

The CERES family of crop growth models shares the same C simulation subroutine (Godwin and Singh, 1998) as CENTURY. CERES divides the fresh organic pool into three sub pools of carbohydrate, cellulose and lignin. Each has its own degradation rate and C : N ratio. The soil humus pool has a much lower turnover rate than the fresh organic pool. It's C and N simulation submodel has been linked into a family of 16 crop growth models under the DSSAT framework (Tsuji *et al.*, 1998). The CERES-Rice model (Ritchie *et al.*, 1998) assumes two types of organic matter-these are the fresh organic matter (FOM) pool, which includes crop residues and green manure, and a more stable organic or humic pool (HUM). The FOM pool is further divided into three arbitrary pools corresponding approximately to the carbohydrate, cellulose and lignin fractions. It is assumed that initially any fresh organic matter is distributed as 20% carbohydrate, 70% cellulose and 10% lignin. The advantage of using this model is that it already includes soil organic matter decomposition routines along with routines describing the relevant crop management options such as water management and applications of organic and inorganic fertilizers.

DAISY (Hansen *et al.*, 1990) is a mechanistic model and was used for simulating trends in total soil C for various long-term experiments. The structure of the

SOM submodel comprises three major organic pools, viz. added organic matter (AOM), soil microbial biomass (SMB) and native soil organic matter (SOM = Total OC – SMB C – AOM C). Turnover processes are described by first order kinetics. Turnover rate coefficients for the different pools are influenced by soil water content, soil temperature and also by clay content. The model was developed for short-term simulations of the agricultural soil-plant-atmosphere system and as such has performed well in several model comparisons (Diekkruger *et al.*, 1995). Jensen *et al.* (1997) reported that DAISY is also capable of simulating long-term trends in soil organic matter reasonably well. Using this model Swinnen *et al.* (1994) estimated that 1.03 to 1.43 t C ha⁻¹ was transferred belowground in wheat of which 0.7 to 0.87 t C ha⁻¹ was rhizodeposits and root decay. Although some studies have suggested that the soil microbial biomass pool can fluctuate dramatically, most recent studies indicate that it is a relatively stable pool, with increases in biomass due to even large organic inputs (up to 10 t straw ha⁻¹) not exceeding 50% (Ocio *et al.*, 1991; Jensen *et al.*, 1997). The CANDY model describes the dynamics of temperature, water, C, and N in arable soils down to a 2m depth (Franko and Mirschel, 2001). Simulation results are produced in daily time steps. It has climate, soil, crop and management modules. The soil module initially provides soil physical properties retrieved from a soil database and takes into account changes in soil organic matter during

long term simulation scenarios with changing land use practices. In CANDY (Franko, 1996) organic matter (C) is held in three sets of pools, fast cycling fresh organic matter (FOM) pool, reproductive organic matter (REP) pool and slow cycling soil organic matter (SOM) pool. Carbon moves out of each pool according to the first order rate equation with rate constants K_F , K_R and K_S adjusted by the environmental factors. Key driving variables are soil physical properties, meteorological data and management information. The main application of the model is the calculation of short term dynamics of nitrogen transformation and long term dynamics of organic matter turnover in arable soils. According to Franko *et al.*, (1997) in most cases CANDY showed the same trend in SOM dynamics as do the experimental results.

The EPIC model is a fully functional agricultural system model and all its components are documented by Williams (1995). It has three organic C/N pools: the fresh organic pool of crop residue and microbial biomass, an active soil humus pool, and a stable soil organic humus pool. Only the fresh residue and the active humus pool are subjected to mineralization. The plant growth simulation is not mechanistic; rather it uses a series of conversion or scaling factors to estimate biomass, leaf area index (LAI), plant height, root growth and yield. EPIC yield estimates were most sensitive to runoff curve number and to maximum rooting depth, both of which influence the soil water balance. Total N and organic C

were satisfactorily estimated by EPIC (Roloff *et al.*, 1998). It has also been used in studies related to nitrate-N, an important component of water quality (Phillips *et al.*, 1993). The soil nitrogen balance in EPIC is dependent on the soil water and soil temperature routines. This model was used to estimate the amount of atmospheric C that could be sequestered by converting marginal grass pastures to pine plantations in the South-Central USA (Lee and Dodson, 1996). Results showed that conversion of 3.6×10^6 ha of marginal grass pasture to pine plantations could sequester 5.6×10^6 Mg C yr^{-1} for the first 25 yr and 1.1×10^6 Mg for the second 25 yr.

NCSOIL simulates C and N transformations in four soil organic pools: a residue pool, a microbial pool (Pool I), an intermediate Pool II with half life of 115 days and C:N ratio of 6, and a more stable Pool III (stable humus) with a C:N ratio of 12 and half life of over 150 years (Molina, 1996). Pool I correspond to the soil microbial biomass as measured by the fumigation method (Nicolardot *et al.*, 1994). Pool I and Pool II represent the potentially mineralizable N, or the biologically active soil organic matter. Each pool may be further divided into labile and resistant fractions. The labile and resistant Pool I fractions have half lives of 2 and 17 days, respectively (Molina *et al.*, 1997). Agricultural management practices such as tillage can change the resistant Pool II fraction to labile (Molina *et al.*, 1983). Decomposition of each pool may be first order or

Monod kinetics. The stable humus pool has a much slower decay rate and is only important for long-term simulation. It is a stand alone model for homogeneous soil conditions. It is also the module of a larger model (NCSWAP) which computes C and N transformations in the soil-water-air-plant system (Clay *et al.*, 1989; Dou and Fox, 1995; Houot *et al.*, 1996).

Cao *et al.*, (1995) presented a mechanistic model in which soil organic carbon was assumed to be partitioned between three main pools based on their rate of decomposition. The carbon in these pools was assumed to be released by decay according to first order reactions. Huang *et al.*, (1998) used two pools in their model to represent soil organic matter, with different potential decomposition rates for each. These could be modified by multipliers representing the influence of soil texture and temperature. Variations in soil water content were not accounted for.

There are several sources of metadata and information on SOM models. CAMASE (Plentinger and Penning de Vries 1996; online at <http://www.bib.wau.nl/camase>) contains information on 98 agroecosystem models which include soil components, and the SOMNET database (Smith *et al.*, 1997a; online at <http://saffron.res.bbsrc.ac.uk/cgi-bin/somnet>) contains metadata on 30 current operational SOM models. Several comprehensive reviews of SOM models have been produced recently. Molina and Smith (1998) reviewed 24

SOMNET registered models for C and N processes in soils. McGill (1996) classified and reviewed ten SOM models with respect to environmental conditions, scale, regulation by soil properties, and compartmentalization. Jenkinson (1990) classified SOM models. Smith *et al.*, (1999) reviewed SOM modelling in tropical ecosystems, covering model use, input requirements and outputs.

The Denitrification-Decomposition (DNDC) model (Li *et al.*, 1992a) is a general model of C and N biogeochemistry in agricultural ecosystems. The model simulates C and N cycling in agro-ecosystems at a daily or sub daily time step. It consists of four interacting submodels: soil climate, plant growth, decomposition and denitrification (Li *et al.*, 1997). In DNDC, soil organic carbon (SOC) resides in four major pools: plant residue (i.e., litter), microbial biomass, humads (or active humus), and passive humus. Each pool consists of two or three sub-pools with different specific decomposition rates. The soil climate submodel simulates soil temperature and moisture profiles based on soil physical properties, daily weather and plant water use. The plant growth submodel calculates daily water and nitrogen uptake by vegetation, root respiration and plant growth and partitioning of biomass into grain, stalk and roots. The decomposition submodel simulates daily decomposition, nitrification, ammonia volatilization and CO₂ production by soil microbes. The submodel calculates turnover rates of soil

organic matter at a daily time step (Li *et al.*, 1992a). The denitrification submodel operates at an hourly time step to simulate denitrification and the production of nitric oxide, nitrous oxide, and dinitrogen. The model has been tested against several field studies. The results related to N₂O and soil organic carbon have been published (Li *et al.*, 1992b; Li *et al.*, 1994; Li *et al.*, 1997). Simulated results showed that DNDC was able to simulate the basic patterns of NO, N₂O, CH₄ and NH₃ fluxes simultaneously (Li, 2000). This feature could be valuable in assessing the net effect of the changing climate or alternative agricultural management on either the atmosphere or agriculture. Linked to GIS databases of climate, soil, vegetation and farming practices, DNDC is ready for regional estimation of trace gas emissions. Soil organic carbon dynamics simulated with the DNDC model were compared to field data from 11 plots at five agricultural field sites (Li *et al.*, 1997). The model captured the overall behaviour of SOC dynamics at all but one of the plots (PG I at Rothamsted). The two plots at the Waite Permanent Rotation Trial (WP-2 and WP-5) showed significant decline in SOC over the 66 years of the study. The Rothamsted Park Grass PG I plot showed a large decline in SOC over the first half of the experiment (1876-1932) and a recovery over the second half. Using this model Davidson and Ackerman (1993) reported that most SOC loss occurred within 20 years of cultivation. Sensitivity simulations with DNDC (Li *et al.*, 1994) showed

SOC approaching an equilibrium value that depends on climate, soil texture and annual carbon inputs with most carbon loss occurring during the first 40 years. A five year run was conducted with the DNDC model at six sites from various climatic zones in the United States. Conventional cropping practices were simulated with the baseline scenario for each site. The annual average loss of SOC was about 6600, 940, 790, 470, -1000 and -1200 kg C ha⁻¹ for the six different sites. The magnitude of change in SOC storage was related to the initial SOC content and climate at each site. Generally, higher initial SOC content and higher temperature favoured SOC loss through enhanced decomposition. The N₂O emission rates appeared to be related to SOC content and annual precipitation. The highest N₂O flux, 22.4 kg N ha⁻¹yr⁻¹, was obtained in Florida where SOC and precipitation were highest.

Trends in soil organic carbon in Rice-Wheat cropping systems

Rice and wheat have been grown as food crops for more than 6000 years in Asia and rice-wheat system has been practiced for 1000 years (Tran and Marathee, 1994). Eight percent of the world population obtains their food from this system. The system occupies 24 million ha of cultivated land in the Asian subtropics. In South Asia, the system occupies about 13 million ha (India, 10 Mha; Pakistan, 2.2 Mha; Bangladesh, 0.5 Mha; and Nepal, 0.5 Mha), extending across the Indo-Gangetic flood plains into Himalayan foothills. It covers about 32% of total rice

area and 42% of total wheat area in these four countries and account for one-quarter to one-third of total rice and wheat production (Ladha *et al.* 2000). It is now found as a major system throughout the Indo Gangetic Plain (IGP).

Recent reports however, indicate that the system is under production fatigue as yields have started declining due to continuous rice-wheat cultivation (Yadav *et al.*, 2000, Ladha *et al.*, 2003). Long term experiments (LTE) set up in the country since 1885 provide opportunities for monitoring long term changes in crop yields and nutrient balances, and identifying the factors associated with such changes (Ladha *et al.*, 2002). Several researchers have studied long-term rice-wheat experiments in Asia (Nambiar, 1994; Cassman *et al.*, 1995; Yadav *et al.*, 1998; 2000; Dawe *et al.*, 2000; Duxbury *et al.*, 2000). The results of some of these experiments have shown declining rice and wheat yields Nambiar, 1995; Brar *et al.*, 1998; Yadav *et al.*, 1998, 2000; Duxbury *et al.*, 2000), whereas in others yields either increased or were maintained (Aggarwal *et al.*, 2000; Yadav *et al.*, 2000; Dawe *et al.*, 2000). Yadav *et al.*, (2000) showed more positive yield trends in rice in treatments with FYM (11 out of 12 LTE) and GM (10 out of 12 LTE) than with 100% mineral NPK (7 out of 12 LTE).

Nutrient imbalance and mining by rice and wheat has lead to problems in some areas. Soil organic matter, is one of the most important components of a field ecosystem which serves as soil conditioner, nutrient source, substrate for

microbial activity, preserver of the environment and major determinant for sustaining of increasing agricultural productivity (Schnitzer, 1991). Decline in soil organic matter has been suggested as a problem with the rice-wheat system (Kataki *et al.*, 2001). In the major rice-wheat regions in north-western India the soil organic C has decreased from 0.5% in sixties to 0.2% at present (Sinha *et al.*, 1998). Ram (2000) reported that twenty years of rice-wheat cropping reduced the SOC from 1.48% to 0.49% and 0.84% in unfertilized and recommended NPK treatments, respectively in Pantnagar. However, the original status of organic carbon was restored by use of 100% NPK+FYM. Puddling of soils for rice destroys soil macro-aggregates leading to substantial losses of SOC in the rice-wheat system (Duxbury, 2001). However many LTE results have demonstrated that judicious applications of fertilizers with appropriate crop rotations and conservation tillage produced the optimum biomass yield and lead to C sequestration in agricultural soils. An experiment conducted at different centres since 1983-91 (Katyal *et al.*, 1998) revealed that continuous rice-wheat cropping increased the organic carbon status at Masodha and Kanpur whereas it remained same at Jabalpur.

The results of the long-term experiment conducted during 1988 to 1997 (Brar *et al.*, 1998) revealed that incorporation of crop residues and FYM alone or in combination with green manure significantly increased the soil organic carbon

content. Cereal crop residues with wider C:N ratio and higher humification coefficient than green manure possibly leave more carbon in soil for conversion to soil organic matter. Yadav *et al.*, (1998) reported that in control plot, organic carbon content of the soil decreased considerably (0.18%) from its initial value (0.37%) after twelve cycles of rice-wheat sequence. However it increased to 0.45% with the application of 100% recommended NPK through fertilizers. The combined use of fertilizers and organic N sources (50:50) further increased the organic carbon levels to 0.56, 0.53 and 0.53 per cent in FYM, wheat straw and green manure treated plots respectively.

There are several national and regional estimates of C sequestration potential in cropland soils (Gupta and Rao, 1994; Lal and Bruce, 1999). Lal and Bruce (1999) estimated the potential of world cropland for sequestering C at 0.4 to 0.6 Pg C yr⁻¹. Similar to global estimates, national estimates on SOC sequestration potential have also been made. Gupta and Rao (1994) estimated the potential for restoration of 35 million ha of wastelands in India at 0.8 Pg and 1.1 Pg in vegetation soil. There is a wide range of recommended management practices for enhancing and sustaining the SOC pool (Magdoff, 1992). Organic C retention in soil is influenced by crop rotation (Biederbeck *et al.*, 1984; Hobbs and Brown, 1965), tillage (Bauer and Black, 1981), residue management (Rasmussen *et al.*, 1980), and fertility (Biederbeck *et al.*, 1984; Rasmussen *et al.*, 1980).

Strategies for C sequestration

Improved management techniques have shown that scientific agriculture can be a solution to these environmental issues in general and specifically to mitigating the greenhouse effect by increasing soil carbon storage and effectively removing CO₂ from the atmosphere. Soil management practices like increasing soil organic carbon content, reduced tillage, manuring, residue incorporation, improving soil biodiversity, micro aggregation, and mulching can play important roles in sequestering carbon in soil.

Conservation tillage

This involves replacing plough based tillage of seedbed preparation in combination with the use of crop (Reicosky and Lindstrom, 1993; Roberts and Chan, 1990). Therefore reducing the intensity and frequency of ploughing and leaving crop residues on the soil surface as mulch are important strategies for enhancing SOC content. Higher SOC in the surface layer under conservation tillage have been reported for soils of West Africa (Lal, 1997), South Africa (Agenbag and Maree, 1989), Australia (So *et al.*, 1999), Argentina (Costanza *et al.*, 1997), Tropical America (Riezebo and Loerts, 1998) and North America (Potter *et al.*, 1997; Dick *et al.*, 1998). The use of conservation tillage practices, those that maintain at least 30% soil surface coverage with harvest residues, promotes surface accumulation of C because of reduced mineralization and

erosion rates (Buschiazzo *et al.*, 1998). Allmaras *et al.* (1999) estimated that as a result of the adoption of conservation tillage and the production of greatly increased amounts of residues, US cropland changed from a C source to a C sink sometime around 1984. In United States the fraction of cropland area under conservation tillage increased from 26% in 1989 to 37% in 1998 (CTIC, 1999). These gains in the adoption of conservation tillage during this 9 year period are encouraging because of their important contributions to soil and water conservation as well as for their potential to sequester SOC.

Doran (1980) reported that organic C concentration in the surface 15 cm of non tilled soils is greater than for tilled soil. According to Campbell *et al.* (1995) continuous wheat cultivation under no tillage condition gained about 1.5 t ha⁻¹ more C than under conventional tillage condition. Organic C in the top 7.5 cm soil were 36% higher in stubble mulch than in conventional tillage, with no differences below 7.5 cm (Rasmussen and Rhode, 1988). Microbial biomass and total C was found to be highest under no till surface soils (0-5 cm), with minimal differences for tillage or depth below 5 cm (Granatstein *et al.*, 1987). The effects of tillage on soil microbial biomass and activity were studied in 1995-1997 in the wheat phase of different cropping rotations that had been established in 1992 under zero tillage or conventional tillage in northern Alberta, Canada (Lupwayi, *et al.*, 1999). Soil microbial biomass was often significantly ($P < 0.05$) higher, but

never significantly lower, under zero tillage than under conventional tillage. However, CO₂ evolution (basal respiration) was usually higher under conventional tillage than under zero tillage, resulting in higher specific respiration (qCO₂) under conventional tillage than under zero tillage. The higher additions but lower losses of labile C under zero tillage mean that more C is sequestered in the soil in the zero-tillage system. Thus, this system contributes less to atmospheric CO₂ than conventional tillage, and that soil organic matter accumulates more under zero tillage. The effect of tillage practices on soil microbial biomass carbon (MBC) while conversion of pasture land to crop rotation by plough tillage was investigated by Aslam *et al.*, (1999). Conversion of permanent pasture to plough tillage cropping resulted in a 45% decline in MBC in the 0-5 cm soil layer. Microbial biomass carbon content ratios in the 5-10 cm layer did not differ significantly among the tillage practices and cropping regimes. At 0-10 cm depth, concentration of MBC was significantly higher in the permanent pasture and no tillage than in the plough tillage treatment. MBC level in autumn was significantly higher than in summer and winter.

Cover crops

The effectiveness of conservation tillage in SOC sequestration is enhanced by the use of cover crops, such as clover and small grains. Frequent use of sod type legumes and grasses in rotation with food crops is an important strategy to

enhance SOC and soil quality (Entry *et al.*, 1996). Gains in SOC by growing cover crops in rotation with food crops have been reported throughout the world including Haryana, India (Chander *et al.*, 1997), southwestern Nigeria (Juo *et al.*, 1996), Syria (Jenkinson *et al.*, 1999), Argentina (Demmi *et al.*, 1986) and Norway (Uhlen and Tveitnes, 1995). Research was conducted to evaluate the potential of cover crops to accumulate SOC (Amado *et al.*, 2001). Soil under maize + velvet bean (cover crop) system had 5.42 t ha^{-1} more C than the fallow/maize system in the 0 to 20 cm soil layer. Cover crops can be grazed and well maintained pastures with controlled grazing at appropriate stocking rate can enhance SOC (Grace *et al.*, 1995). Neill *et al.* (1997) observed that SOC increased in 14 of 18 pastures and the magnitude of increase in some cases was as much as 18 Mg C ha^{-1} to a 30 cm depth. Strategies that increase the cropping intensity such as the use of rotations with winter cover crops to increase the amount of biomass C returned to the soil can affect the size, turnover and vertical distribution of both active and passive pools of SOC (Franzluebbers *et al.*, 1995). Sainju *et al.*, (2002) reported that concentrations of soil organic C was greater with rye, hairy vetch and crimson clover cover crops than without a cover crop.

Crop rotation

Effects of crop rotation on SOC content have been widely reflected in numerous long term experiments. Cropping systems provide an opportunity to produce

more biomass C than in a monoculture system and to thus increase SOC sequestration. Chander *et al.*, (1997) studied soil organic matter under different crop rotations for 6 years and found that inclusion of green manure crop of *Sesbania aculeata* in the rotation improved soil organic matter status and microbial C increased from 192 mg kg⁻¹ soil in pearl millet-wheat fallow rotation to 256 mg kg⁻¹ soil in pearl millet-wheat green manure rotation. Franzluebbers *et al.*, (1995) observed that mineralizable C and microbial biomass carbon (MBC) averaged 18% greater in rotation than in monoculture, probably due to greater C input via crop roots and residues in rotation and a shorter fallow. Benefits of crop rotations in managing SOC are documented by several long term experiments in the United States (Anderson *et al.*, 1990). Legume-based cropping systems could help to increase crop productivity and soil organic matter levels, thereby enhancing soil quality, as well as having the additional benefit of sequestering atmospheric C (Gregorich *et al.*, 2001). The quantity of C below the plough layer in legume-based rotation was 40% greater than that in monoculture. The soil organic matter below the plough layer in soil under the legume-based rotation appeared to be in a more biologically resistant form (i.e., higher aromatic C content) compared with that under monoculture. In Ohio, Dick *et al.*, (1998) observed that soil under a meadow based rotation contained 15 Mg ha⁻¹ more SOC in the top 30 cm layer than a corn-soybean rotation. Granatstein *et al.*,

(1987) studied the rotation effects on soil microbial biomass and total C. According to them a rotation with two legume crops had the highest total C and biomass levels. Similar results were reported by Lupwayi *et al.*, (1999). According to them plots preceded by summer fallow, especially under conventional tillage, usually had the lowest microbial biomass and plots preceded by legume crops had higher microbial biomass than other treatments.

Incorporation of crop residue in soil

Management of crop residues is of primary importance. Incorporation of crop residues in soil leads to increased soil organic matter levels (Stewart, 1993). Within a cropping system, the equilibrium level of SOC can be related linearly to amount of crop residue applied to the soil (Rasmussen *et al.*, 1980; Follett *et al.*, 1987). Aulakh and Doran (2002) reported that rice and wheat residues help in sequestering C in agricultural soils. According to them incorporation of wheat residue resulted in more SOC than with rice residue. Paustian *et al.*, (1992) observed that lignin content of the residue has a strong positive effect on SOC accumulation. In a field experiment, soybean, mustard, chickpea and wheat residues and urban refuse compost were chopped to 3-5 cm lengths, mixed with farmyard manure, pyrites and rock phosphate and incorporated at 10 t ha^{-1} 2.5 months before sowing a kharif crop of rice and a rabi crop of wheat. Soil microbial biomass carbon was greatest in plots treated with the wheat straw

mixture, irrespective of grain crop. Compared with applying inorganic NPK fertilizer, the phosphocompost mixtures increased soil microbial biomass carbon by 12-24% and 27-53% after harvesting rice and wheat, respectively (Manna and Ganguly, 1998).

Measurements in 1996 indicated that seven years of residue application had a positive effect on SOC content in the 0 to 10 cm depth (Duiker and Lal, 1999). Similar results were reported by Havlin *et al.*, (1990). Incorporation of crop residues significantly increased soil organic C content in a long term field experiment conducted in rice-wheat cropping system (Singh *et al.*, 2000). Cereal crop residues with high C:N ratio leave more C in soil for conversion to soil organic matter. A 60-day greenhouse simulation experiment was carried out to study the effects of straw placement on soil MBC dynamics. The treatments included straw addition + buried (T1); straw addition + mineral N (T2); and straw addition + tillage (T3). Straw was either buried in the soil or placed on the surface. Straw placement and addition of external mineral N sources (Urea, 46% N) affected MBC. Rate of MBC fixation was more in buried straw than in surface placed straw at all sampling dates in both soils. Addition of an external N source significantly increased MBC level (Chilima, *et al.*, 2002). Besides above-ground crop residues, other important organic materials for enhancing the SOC content are below-ground root biomass and total biomass produced by weeds

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(Follett, 2001). Lal *et al.*, (1998) estimated the amount of residue C produced on US cropland is about 447.3 MMTC, including above-ground residues and below-ground biomass plus weeds. By assuming that 50% of the residue C can be efficiently managed and then with C sequestration efficiency from 5 to 10%, the amount of SOC sequestered is estimated as 11.2-22.4 MMTC yr⁻¹.

Nutrient management

On a long-term basis, increased crop yield and organic matter returned to the soil with judicious fertilizer application result in higher SOC content and biological activity than under controlled conditions (absence of fertilizers). Lal *et al.*, (1998) summarized the results of a number of studies and concluded that fertility management practices can enhance the SOC content at the rate of 50-150 kg ha⁻¹ yr⁻¹. A study conducted by Ryan *et al.* (1998) reported that amount of organic matter increased with increasing rates of N fertilizers (0-90 kg ha⁻¹). In a dryland annual cropping study after 11 crops Halvorson *et al.* (1999) observed that fertilizer N rates of 67 and 134 kg N ha⁻¹ yr⁻¹ resulted in 140 and 182 kg ha⁻¹ yr⁻¹ more SOC, respectively, in the 0-15 cm depth than for the zero N treatment. Phosphorus fertilizer also has a beneficial impact on organic soil C (Kumar and Yadav, 2001). They observed that after 20 years of continuous rice-wheat cropping, soil organic C increased by 35, 27 and 20% in plots receiving 120-35-33, 120-35-0, and 80-35-33 kg ha⁻¹ NPK, respectively, relative to the initial value

of 4.5 g C kg^{-1} soil in 1977. In contrast, organic C declined in the unfertilized treatment by 62% compared with the initial level and by 49% in the treatment receiving 120 kg ha^{-1} alone. The effects of fertilizer applications on the microbial biomass C and N levels, were studied in an acid soil under subalpine *Eucalyptus pauciflora* forest near Canberra, Australia (Hossain, *et al.*, 1995). Fertilizer treatments (lime + P) and (N + P) significantly affected soil microbial biomass C contents. The (N + P) treatment significantly increased biomass C only at 0-2.5 cm depth, whereas from 0-10 cm the biomass C was more than double the values in the (lime + P) treatment. Integrated addition of inorganics with organics through farmyard manure, green manure and crop residues increased the organic carbon content significantly over control followed by recommended dose of NPK (Sharma *et al.*, 2001). According to Rasmussen and Rohde (1988) applied N increased soil C linearly on plots. But soil C was higher on plots with no previous S than on comparable plots with previous Sommerfeldt *et al.* (1988) reported that the amounts of organic matter (OM) in the soil were correlated to the total designated amounts of manure applied and OM increase in the surface 30 cm of soil followed a Michaelis-Menten type of function, over the range of 30 to 180 Mg ha^{-1} of manure. The rate of OM accumulation in the soil, was greater with greater levels of manure application but decreased with years of application. A long-term (16 years) field experiment was conducted in Jiangsu, China, to

investigate the effects of manure application on soil microbial biomass carbon (MBC). Although the application rate of N, P and K in each sub-treatments were equal, the contents of MBC, in 0-5 and 5-10 cm depth layer followed the treatments in the order: fertilizers + pig manure > fertilizers + straw > fertilizers + green manure > chemical fertilizers > control (Xu et al., 2002).

Materials and Methods

Field experiments

Site

The experiments for monitoring soil carbon and microbial biomass were conducted with rice and wheat for two years in the farm of Indian Agricultural Research Institute (IARI), New Delhi in 2001-2003 (28°40' N and 77°12' E altitude of 228 m). The climate of Delhi is subtropical semiarid with hot and dry summers and cold winters under average climatic conditions. The area receives 750 mm annual rainfall, about 80% of which occurs from June to September. The mean annual maximum temperature is 35°C while the mean annual minimum temperature is 18°C. The soils are well drained with the groundwater table at 6.6 and 10m depth during the rainy and summer seasons, respectively. The alluvial soil of experimental site was Typic Haplustept with pH 8.12 and silty clay loam texture. The physico-chemical properties of the soil are given in Table 2.

Table 2. Physico-chemical properties of the experimental soil

Parameters	Values
Sand (%)	40
Silt (%)	32
Clay (%)	28
Texture class	Silty clay loam
Bulk density (g cm^{-3})	1.4
Hydraulic conductivity (cm day^{-1})	4.8
Field capacity (%)	20.5
pH (1:2::Soil:Water)	8.0
Electrical conductivity (d S m^{-1})	0.78
CEC ($\text{C mol (p}^+) \text{ kg}^{-1}$)	7.3
Organic carbon (%)	0.62
Available N (kg ha^{-1})	250
$\text{NH}_4\text{-N}$ (mg kg^{-1} soil)	38.9
$\text{NO}_3\text{-N}$ (mg kg^{-1} soil)	58.1
Available P (kg ha^{-1})	56.5
Available K (kg ha^{-1})	406

Experimental design and treatments

Rice:

Field experiments were conducted with rice variety Pusa 44 during kharif 2001 and with Pusa Sugandh 3 during kharif 2002. The experiments were laid out in a split plot design. The main plots comprise of two tillage treatments viz.

puddled and non-puddled. The subplots included 7 treatments each with 3 replications in plots of 7.5 m long and 5.25 m wide (Table 3).

Table 3: Treatments in rice

Treatments	Tillage	N source
T1	Puddled	Control (no N)
T2	Puddled	100% NPK
T3	Puddled	100% NPK (25% substituted by FYM)
T4	Puddled	100% NPK + Green manure
T5	Puddled	100% NPK + Crop residues
T6	Puddled	100% organic source (50% FYM + 25% Biofertilizer + 25% Green manure)
T7	Puddled	Blank plot
T8	Non puddled	Control (no N)
T9	Non puddled	100% NPK
T10	Non puddled	100% NPK (25% substituted by FYM)
T11	Non puddled	100% NPK + Green manure
T12	Non puddled	100% NPK + Crop residues
T13	Non puddled	100% organic source (50% FYM + 25% Biofertilizer + 25% Green manure)
T14	Non puddled	Blank plot

In the year 2001, transplanting was carried out on July 24, 2001 at 20 by 15 cm spacing. In the non-puddled plots rice was directly sown on June 26, 2001.

Nitrogen as urea was applied at the rate of 120 kg N ha⁻¹ in three splits, half at 17 days after transplanting/sowing (DAT/DAS) and the remaining half in two equal splits at 37 and 61 DAT/DAS.

In the year 2002 transplanting was done on July 28, 2002 while direct seeding was carried out on June 30, 2002. Three splits of nitrogen were applied at 11, 29 and 62 DAT/DAS, respectively. In order to maintain the saturation moisture regime irrigation was provided every two days throughout the cropping period. Farmyard manure (FYM) was incorporated in soil 2 weeks before transplanting at the rate 6 t ha⁻¹. On fresh weight basis it contained 0.52% N, 0.38% P and 0.42% K. Green manuring crop (Subabool) (2 t ha⁻¹) was incorporated in soil before transplanting. 10⁹ cells gm⁻¹ carrier based culture of *Azospirillum spp.* CD strain was used on seed at the time of sowing as biofertilizer. Crop residues of the previous crop were incorporated before sowing in the treatment with crop residues (T5 and T12).

Wheat:

Wheat variety HD-2687 was used for both the years. In the first year wheat was sown on December 7, 2001 in rows at 22.5 cm apart. Each plot was divided into two parts one is where tillage was done and another with no tillage. So the design changed from split plot to split split plot (Table 4). Urea was applied at the rate of 120 kg N ha⁻¹ in three splits, half at 11 (DAS) and the

remaining half in two equal splits at 31 and 84 DAS. Five irrigations were applied at 25, 62, 80, 97 and 117 DAS. The second year wheat was sown on December 19, 2002 and fertilizer was applied at 0, 19 and 70 DAT. FYM, green manure, crop residue and biofertilizer was applied in the same way as in rice.

Soil sampling and analysis

Soil samples from 0-15 and 15-30 cm depth were collected in 3 locations from each plot at different crop growth stages. The entire volume of soil was mixed thoroughly and subsamples were used for analysis. Fresh soil was used for determining microbial biomass carbon (MBC). Soil was air-dried for 7 days, sieved through 0.2 mm screen, mixed and stored in sealed plastic jars for further analysis. Representative subsamples were drawn to determine various physico-chemical properties using standard procedures (Table 5).

Table 4: Treatments in wheat

Treatments	Tillage	N source
T1	Puddled tilled	Control (no N)
T2	Puddled tilled	100% NPK
T3	Puddled tilled	100% NPK (25% substituted by FYM)
T4	Puddled tilled	100% NPK + Green manure
T5	Puddled tilled	100% NPK + Crop residues
T6	Puddled tilled	100% organic source (50% FYM + 25% Biofertilizer + 25% Green manure)
T7	Puddled tilled	Blank plot
T8	Puddled no	Control (no N)

	tilled		
T9	Puddled tilled	no	100% NPK
T10	Puddled tilled	no	100% NPK (25% substituted by FYM)
T11	Puddled tilled	no	100% NPK + Green manure
T12	Puddled tilled	no	100% NPK + Crop residues
T13	Puddled tilled	no	100% organic source (50% FYM + 25% Biofertilizer + 25% Green manure)
T14	Puddled tilled	no	Blank plot
T15	Non tilled	puddled	Control (no N)
T16	Non tilled	puddled	100% NPK
T17	Non tilled	puddled	100% NPK (25% substituted by FYM)
T18	Non tilled	puddled	100% NPK + Green manure
T19	Non tilled	puddled	100% NPK + Crop residues
T20	Non tilled	puddled	100% organic source (50% FYM + 25% Biofertilizer + 25% Green manure)
T21	Non tilled	puddled	Blank plot
T22	Non tilled	puddled no	Control (no N)
T23	Non tilled	puddled no	100% NPK
T24	Non tilled	puddled no	100% NPK (25% substituted by FYM)

T25	Non puddled no tilled	100% NPK + Green manure
T26	Non puddled no tilled	100% NPK + Crop residues
T27	Non puddled no tilled	100% organic source (50% FYM + 25% Biofertilizer + 25% Green manure)
T28	Non puddled no tilled	Blank plot

Determination of soil microbial biomass carbon (MBC)

Soil microbial biomass carbon was estimated using chloroform fumigation extraction method (Whit *et al.*, 2000). Extractable organic carbon in fumigated and unfumigated soil extracts was determined using potassium dichromate ($K_2Cr_2O_7$) method. Soil microbial biomass carbon was calculated using equation $SMBC = E_c / K_{Ec}$ where E_c = organic carbon extracted from fumigated soil – organic carbon extracted from unfumigated soil. $K_{Ec} = 0.45$

Simultaneously absorbance (E_{280}) of the K_2SO_4 extract from fumigated and unfumigated soils was measured at 280 nm (Nunan *et al.*, 1998) using a UV visible spectrophotometer (Schimadzee Ltd. Japan). The data used for building relationship between absorbance and dichromate method were the means of triplicate determination $\pm$ standard error.

Table 5. Methods of soil analysis

Parameters	Method	Reference
Mechanical analysis	Bouyoucos hydrometer	Piper (1966)
Water holding capacity	Gravimetric	Piper (1966)
Hydraulic conductivity	Constant head method	Klute and Dirksen (1986)
PH (1:2 :: Soil:Water)	Potentiometric	Jackson (1967)
Electrical conductivity (1:2 :: Soil:Water)	Conductimetric	Jackson (1967)
Cation exchange capacity	BaCl ₂	Jackson (1967)
Organic carbon	Walkley and Black	Jackson (1967)
Available P	Olsen method	Olsen <i>et al.</i> (1954)
Available K	NH ₄ OAC (pH 7.0)	Jackson (1967)
Total N	Kjeldahl	Bremner (1965)
Available N	Alkaline permanganate method	Subbiah and Asija (1956)
NH ₄ -N	Indophenol blue method	Keeney and Nelson (1982)
NO ₃ -N	Phenol disulphonic acid method	Ghosh <i>et al.</i> , (1983)
Microbial biomass C	Fumigation extraction method	Whit <i>et al.</i> , (2000)

Carbon dynamics in InfoCrop model

The InfoCrop model used by Daryei (2003) was used for the following study. The crop module describing above-ground carbon dynamics has already been calibrated by Daryei (2003). Although InfoCrop has detailed carbon

dynamics for the crop it does not include a soil carbon balance module. The latter was developed based on the literature review and inputs from our own field experiments.

Calibration and validation of the model

The carbon module of the InfoCrop model was calibrated with the data from an independent field experiments conducted earlier in IARI farm for two years (1999-2001) with rice-wheat cropping system (Pathak et al., 2002 and 2003). The experiment included two crops per year, rice (July-October) and wheat (November-March), with 8 treatments arranged in a factorial randomized block design with three replications (Table 3 and 4) in plots of 6 m long and 5 m wide. The alluvial soil of experimental site was Typic Haplustept with pH 8.12 and clay loam in texture. Treatments in rice and wheat included four sources of N: 1) urea, 2) urea + FYM, and 3) no N control. Two types of irrigation practices were followed: (1) saturated soil moisture regime giving 30 irrigations in rice; and 5 irrigations in wheat (treatments 1, 2, 3, and 4) and (2) intermittent wetting and drying giving 20 irrigations in rice and 3 irrigations in wheat (treatments 5, 6, 7 and 8). All the irrigations were of 5 ± 2 cm depth.

The agronomic management followed in the experiments was input in the simulation model. Observations taken from this experiment such as grain yield, total biomass yield, methane (CH_4) emission and CO_2 emission were simulated

by the model and accordingly the model was validated. The details of these experiments have been given in Pathak et al. (2002), Pathak et al. (2003) and Rastogi et al. (Personal communication).

Since these experiments dealt only with short-term changes in carbon dynamics, a long-term experiment (1985-1997) done earlier in the Indo-Gangetic plains was also used to validate the model. This experiment was conducted in rice-wheat system on a Typic Ustochrept at the experimental farm of PAU, Ludhiana (Bhandari et al., 2002). The soil of the experimental site was loamy sand in texture with pH 8.15, OC 0.38%, and CEC 13.5 cmol (p⁺) kg. The treatments were:

- (1) 100% NPK
- (2) 50% NPK
- (3) 75% NPK 50% NPK + FYM in rice and 100% NPK in wheat
- (4) 50% NPK + green manure in rice and 100% NPK in wheat
- (5) 75% NPK + green manure in rice and 75% NPK in wheat
- (6) 75% NPK + FYM in rice and 75% NPK in wheat, and
- (7) Control.

The details of the agronomic management were not fully documented by the authors. Hence, for simulation it was assumed that the same variety of rice

and wheat was used every year, and the sowing dates/transplanting dates and irrigation management was standard for the region.

Extrapolation

The validated model for carbon dynamics was used to study long-term effects (10 years) of the following treatments on the carbon dynamics of the rice-wheat system at representative locations in the Indo-Gangetic plain. The locations selected were Delhi, Karnal, Varanasi and Calcutta. The following treatments were simulated:

- (1) Control
- (2) 100% NPK
- (3) 75% NPK + 25% FYM
- (4) Blank plot

Long-term change in yield, soil organic carbon, methane emission and CO₂ emission were simulated for these representative stations of the Indo-Gangetic plain. The soil properties including organic carbon were initialized for the first rice season and then the model was allowed to run continuously for 10 crop seasons of rice followed by wheat. Standard agronomic practices of variety, sowing date and water management were followed. Rice was transplanted on a puddled soil. Both crops were irrigated as per the recommended practices.

Results and Discussion

Dynamics of soil organic carbon (SOC)

Rice 2001

Fertilizer treatments significantly affected the organic carbon content of 0-15 cm soil layer at different crop growth stages. Organic carbon content of blank plot was 0.63% at the time of sowing which is slightly higher than control (Table 6). Organic carbon content of other treatment plots was higher as compared to the control plot. By tillering stage, organic carbon of puddled soils decreased to the level of non-puddled in most treatments (Table 7). In this year, maximum organic carbon (0.68%) was recorded in green manure treatment at flowering stage followed by FYM treatment (0.66%) at the time of sowing of the crop (Table 8). At harvest, soil organic carbon values of FYM and green manure treatments were at par (Table 9). At puddled site highest organic carbon (0.76%) content was recorded in FYM treatment at flowering stage (Table 8) while it is in green manure treatment (0.62%) at tillering stage in non-puddled soil (Table 7). In general, puddle soils had higher organic carbon content than the non-puddled ones.

Application of organic matter had no effect on organic carbon content of 15-30 cm soil layer (Tables 10, 11, 12 and 13). But soil organic carbon content of puddled soil was significantly higher than that of non-puddled soil at this depth at all times.

Table 6. Organic Carbon (OC) content of rice soil (0-15 cm) at time of sowing in 2001

Fertilizer treatment	Organic carbon (%)		Mean
	Puddled	Nonpuddled	
Control	0.61	0.54	0.58
100% NPK	0.64	0.56	0.60
100% NPK (25% substituted by FYM)	0.73	0.59	0.66
100% NPK + Green manure	0.66	0.6	0.63
100% NPK + Crop residues	0.63	0.52	0.58
100% organic source	0.66	0.58	0.62
Blank plot	0.63	0.53	0.58
Mean	0.65	0.56	

LSD ($P = 0.05$): Fertilizer – 0.04; Puddling - 0.02

Table 7. Organic Carbon (OC) content of rice soil (0-15 cm) at tillering stage in 2001

Fertilizer treatment	Organic carbon (%)		Mean
	Puddled	Nonpuddled	
Control	0.60	0.52	0.56
100% NPK	0.56	0.54	0.55
100% NPK (25% substituted by FYM)	0.55	0.60	0.58
100% NPK + Green manure	0.58	0.62	0.60
100% NPK + Crop residues	0.60	0.53	0.56
100% organic source	0.56	0.59	0.58
Blank plot	0.58	0.57	0.58
Mean	0.57	0.57	

LSD ($P = 0.05$): Fertilizer – 0.05; Puddling - 0.06

Table 8. Organic Carbon (OC) content of rice soil (0-15 cm) at flowering stage in 2001

Fertilizer treatment	Organic carbon (%)		Mean
	Puddled	Nonpuddled	
Control	0.61	0.52	0.57
100% NPK	0.64	0.56	0.60
100% NPK (25% substituted by FYM)	0.70	0.58	0.64
100% NPK + Green manure	0.76	0.59	0.68
100% NPK + Crop residues	0.64	0.55	0.60
100% organic source	0.68	0.56	0.62
Blank plot	0.66	0.55	0.60
Mean	0.67	0.56	

LSD ($P = 0.05$): Fertilizer – 0.04; Puddling - 0.01

Table 9. Organic Carbon (OC) content of rice soil (0-15 cm) after harvesting of rice in 2001

Fertilizer treatment	Organic carbon (%)		Mean
	Puddled	Nonpuddled	
Control	0.60	0.55	0.58
100% NPK	0.67	0.57	0.62
100% NPK (25% substituted by FYM)	0.70	0.58	0.64
100% NPK + Green manure	0.70	0.58	0.64
100% NPK + Crop residues	0.66	0.56	0.61
100% organic source	0.68	0.56	0.62
Blank plot	0.68	0.56	0.62
Mean	0.67	0.57	

LSD ($P = 0.05$): Fertilizer – 0.03; Puddling - 0.04

Table 10. Organic Carbon (OC) content of rice soil (15-30 cm) at time of sowing in 2001

Fertilizer treatment	Organic carbon (%)		Mean
	Puddled	Nonpuddled	
Control	0.38	0.31	0.35
100% NPK	0.39	0.34	0.37
100% NPK (25% substituted by FYM)	0.45	0.36	0.41
100% NPK + Green manure	0.45	0.35	0.40
100% NPK + Crop residues	0.42	0.33	0.38
100% organic source	0.40	0.31	0.36
Blank plot	0.40	0.32	0.36
Mean	0.41	0.33	

LSD ($P = 0.05$): Fertilizer – NS; Puddling - 0.01

Table 11. Organic Carbon (OC) content of rice soil (15-30 cm) at tillering stage in 2001

Fertilizer treatment	Organic carbon (%)		Mean
	Puddled	Nonpuddled	
Control	0.39	0.31	0.35
100% NPK	0.39	0.33	0.36
100% NPK (25% substituted by FYM)	0.40	0.36	0.38
100% NPK + Green manure	0.42	0.36	0.39
100% NPK + Crop residues	0.41	0.32	0.37
100% organic source	0.40	0.34	0.37
Blank plot	0.40	0.31	0.36
Mean	0.40	0.33	

LSD ($P = 0.05$): Fertilizer – NS; Puddling - 0.02

Table 12. Organic Carbon (OC) content of rice soil (15-30 cm) at flowering stage in 2001

Fertilizer treatment	Organic carbon (%)		Mean
	Puddled	Nonpuddled	
Control	0.39	0.31	0.35
100% NPK	0.41	0.33	0.37
100% NPK (25% substituted by FYM)	0.40	0.34	0.37
100% NPK + Green manure	0.41	0.36	0.39
100% NPK + Crop residues	0.39	0.30	0.35
100% organic source	0.38	0.32	0.35
Blank plot	0.41	0.31	0.36
Mean	0.40	0.32	

LSD ($P = 0.05$): Fertilizer – NS; Puddling - 0.02

Table 13. Organic Carbon (OC) content of rice soil (15-30 cm) after harvesting of rice in 2001

Fertilizer treatment	Organic carbon (%)		Mean
	Puddled	Nonpuddled	
Control	0.39	0.30	0.35
100% NPK	0.37	0.33	0.35
100% NPK (25% substituted by FYM)	0.40	0.34	0.37
100% NPK + Green manure	0.40	0.35	0.38
100% NPK + Crop residues	0.39	0.32	0.36
100% organic source	0.39	0.33	0.36
Blank plot	0.38	0.32	0.35
Mean	0.39	0.33	

LSD ($P = 0.05$): Fertilizer – NS; Puddling - 0.02

Soil organic carbon at puddled site was 0.41% at sowing, 0.4% at tillering and flowering and 0.39% at the time of harvesting of rice

Wheat 2001

The response of soil organic carbon to fertilizer and manure application was observed in wheat also. At 0-15 cm depth, blank plot recorded less organic carbon as compared to fertilized plots but significantly higher than that of control plot (Table 14). Addition of organic matter raised the level of soil organic carbon in all treatments, irrespective of puddling and tillage. At CRI stage highest organic carbon (0.68%) was recorded in FYM, green manure and 100% organic source treatments, which are all organically treated plots (Table 14) while at tillering stage FYM and green manure treatments showed high levels (0.7%) of soil organic carbon followed by 100% organic source treatment (0.68%) (Table 15). Crop residue treatment showed similar organic carbon (0.67%) as in 100% NPK treatment (Table 15) at this stage. At flowering stage green manure treatment recorded maximum soil organic carbon (0.71%) (Table 16). Application of FYM, green manure, crop residue and biofertilizers resulted in 7.8%, 10.9%, 4.7% and 6.3% higher organic carbon content of soil than control. In crop residue treatment soil organic carbon was maximum (0.68%) at harvesting stage of wheat (Table 17). At puddled tilled site soil organic carbon of 0-15 cm soil layer was highest in FYM and green manure treatment (0.73%) at flowering stage of the crop while

Table 14. Organic Carbon (OC) content of wheat soil (0-15 cm) at CRI stage in 2001

Fertilizer treatment	Organic carbon (%)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	0.59	0.59	0.59	0.60	0.60	0.60	0.60
100% NPK	0.66	0.59	0.63	0.66	0.61	0.64	0.63
100% NPK (25% substituted by FYM)	0.70	0.68	0.69	0.67	0.66	0.67	0.68
100% NPK + Green manure	0.69	0.72	0.71	0.62	0.68	0.65	0.68
100% NPK + Crop residues	0.69	0.60	0.65	0.67	0.66	0.67	0.66
100% organic source	0.70	0.68	0.69	0.68	0.67	0.68	0.68
Blank plot	0.66	0.65	0.66	0.59	0.64	0.62	0.64
Mean	0.67	0.64		0.64	0.65		

LSD ($P = 0.05$): Fertilizer - 0.02; Tillage - NS; Puddling - NS

Table 15. Organic Carbon (OC) content of wheat soil (0-15 cm) at tillering stage in 2001

Fertilizer treatment	Organic carbon (%)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	0.57	0.62	0.60	0.60	0.63	0.62	0.61
100% NPK	0.69	0.68	0.69	0.65	0.66	0.66	0.67
100% NPK (25% substituted by FYM)	0.72	0.70	0.71	0.68	0.68	0.68	0.70
100% NPK + Green manure	0.69	0.70	0.70	0.69	0.70	0.70	0.70
100% NPK + Crop residues	0.68	0.68	0.68	0.66	0.67	0.67	0.67
100% organic source	0.71	0.68	0.70	0.63	0.68	0.66	0.68
Blank plot	0.65	0.63	0.64	0.61	0.64	0.63	0.63
Mean	0.67	0.67		0.65	0.67		

LSD ($P = 0.05$): Fertilizer – 0.02; Tillage- NS; Puddling - NS

Table 16. Organic Carbon (OC) content of wheat soil (0-15 cm) at flowering stage in 2001

Fertilizer treatment	Organic carbon (%)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	0.63	0.68	0.66	0.61	0.63	0.62	0.64
100% NPK	0.64	0.66	0.65	0.66	0.67	0.67	0.66
100% NPK (25% substituted by FYM)	0.73	0.70	0.72	0.67	0.66	0.67	0.69
100% NPK + Green manure	0.73	0.71	0.72	0.71	0.69	0.70	0.71
100% NPK + Crop residues	0.67	0.67	0.67	0.70	0.65	0.68	0.67
100% organic source	0.70	0.68	0.69	0.64	0.69	0.67	0.68
Blank plot	0.66	0.63		0.60	0.64	0.62	0.63
Mean	0.68	0.68		0.66	0.66		

LSD ($P = 0.05$): Fertilizer – 0.02; Tillage- NS; Puddling - NS

Table 17. Organic Carbon (OC %) content of wheat soil (0-15 cm) at harvesting in 2001

Fertilizer treatment	Organic carbon (%)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	0.64	0.65	0.65	0.64	0.64	0.64	0.64
100% NPK	0.64	0.67	0.66	0.66	0.66	0.66	0.66
100% NPK (25% substituted by FYM)	0.71	0.67	0.69	0.76	0.67	0.72	0.70
100% NPK + Green manure	0.68	0.71	0.70	0.68	0.68	0.68	0.69
100% NPK + Crop residues	0.68	0.68	0.68	0.68	0.66	0.67	0.68
100% organic source	0.71	0.70	0.71	0.71	0.67	0.69	0.70
Blank plot	0.68	0.63	0.66	0.68	0.65	0.67	0.66
Mean	0.68	0.67		0.69	0.66		

LSD ($P = 0.05$): Fertilizer – 0.02; Tillage- NS; Puddling - NS

green manure treatment in nonpuddled tilled soil showed highest value of soil organic carbon (0.71%) at this stage (Table 16). In both puddled and nonpuddled soil tillage treatments have not significantly affected soil organic carbon content.

The organic amendments significantly affected soil organic carbon content at 15-30 cm depth. Green manure treatment showed maximum soil organic carbon (0.39%) in this layer at CRI stage and also at the time of harvesting (Tables 18 and 21). At tillering and flowering stages maximum soil organic carbon was recorded in green manure treatment with values of 0.38% and 0.37% (Tables 19 and 20). In this layer also organic carbon content of blank plot was found to be less than other treatments. Organic carbon content of wheat soil, however, was not affected by tillage as well as puddling in previous rice.

Rice 2002

Soil organic carbon was significantly affected by application of fertilizer and organic matter in this year. Blank plot had almost similar organic carbon content as control. The FYM treatment recorded highest values of soil organic carbon at all the crop growth stages and the maximum value was 0.72% at the time of sowing (Table 22). Crop residue treatment showed 5% more soil organic carbon than control at tillering and flowering stage of the crop (Tables 23 and 24). Plots receiving the entire amount of nutrients through organic sources also showed high (0.65%) organic carbon content at flowering stage of the crop (Table 24).

Table 18. Organic Carbon (OC) content of wheat soil (15-30 cm) at CRI stage in

Fertilizer treatment	Organic carbon (%)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	0.38	0.34	0.36	0.35	0.34	0.35	0.35
100% NPK	0.37	0.38	0.38	0.37	0.36	0.37	0.37
100% NPK (25% substituted by FYM)	0.40	0.37	0.39	0.38	0.35	0.37	0.38
100% NPK + Green manure	0.42	0.42	0.42	0.37	0.35	0.36	0.39
100% NPK + Crop residues	0.39	0.36	0.38	0.35	0.36	0.36	0.37
100% organic source	0.35	0.37	0.36	0.35	0.34	0.35	0.35
Blank plot	0.34	0.35	0.35	0.35	0.34	0.35	0.35
Mean	0.38	0.37		0.36	0.35		

2001

LSD ($P = 0.05$): Fertilizer – 0.02; Tillage- NS; Puddling- 0.01

Table 19. Organic Carbon (OC) content of wheat soil (15-30 cm) at tillering stage in 2001

Fertilizer treatment	Organic carbon (%)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	0.36	0.32	0.34	0.34	0.34	0.34	0.34
100% NPK	0.36	0.35	0.36	0.36	0.34	0.35	0.35
100% NPK (25% substituted by FYM)	0.40	0.37	0.39	0.35	0.35	0.35	0.37
100% NPK + Green manure	0.38	0.39	0.39	0.36	0.37	0.37	0.38
100% NPK + Crop residues	0.37	0.37	0.37	0.35	0.36	0.36	0.36
100% organic source	0.39	0.36	0.38	0.36	0.35	0.36	0.37
Blank plot	0.35	0.35	0.35	0.34	0.35	0.35	0.35
Mean	0.37	0.36		0.35	0.35		
LSD ($P = 0.05$): Fertilizer – 0.02; Tillage- NS; Puddling- NS							

**Table 20. Organic Carbon (OC) content of wheat soil (15-30 cm) at flowering stage
in 2001**

Fertilizer treatment	Organic carbon (%)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	0.35	0.34	0.35	0.34	0.35	0.35	0.35
100% NPK	0.39	0.35	0.37	0.36	0.36	0.36	0.37
100% NPK (25% substituted by FYM)	0.36	0.36	0.36	0.35	0.35	0.35	0.36
100% NPK + Green manure	0.38	0.36	0.37	0.38	0.34	0.36	0.37
100% NPK + Crop residues	0.37	0.35	0.36	0.35	0.36	0.36	0.36
100% organic source	0.40	0.34	0.37	0.34	0.35	0.35	0.36
Blank plot	0.36	0.34	0.35	0.33	0.33	0.33	0.34
Mean	0.37	0.35		0.35	0.35		

LSD ($P = 0.05$): Fertilizer – 0.02; Tillage- 0.01; Puddling- NS

Table 21. Organic Carbon (OC) content of wheat soil (15-30 cm) at harvesting in 2001

Fertilizer treatment	Organic carbon (%)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	0.35	0.34	0.35	0.35	0.34	0.35	0.35
100% NPK	0.38	0.37	0.38	0.38	0.35	0.37	0.37
100% NPK (25% substituted by FYM)	0.39	0.37	0.38	0.37	0.36	0.37	0.37
100% NPK + Green manure	0.40	0.41	0.41	0.38	0.37	0.38	0.39
100% NPK + Crop residues	0.36	0.35	0.36	0.36	0.35	0.36	0.36
100% organic source	0.39	0.39	0.39	0.37	0.35	0.36	0.38
Blank plot	0.35	0.33	0.34	0.36	0.34	0.35	0.35
Mean	0.37	0.37		0.37	0.35		

LSD ($P = 0.05$): Fertilizer – 0.01; Tillage- 0.01; Puddling- 0.01

Table 22. Organic Carbon (OC) content of rice soil (0-15 cm) at time of sowing in 2002

Fertilizer treatment	Organic carbon (%)		Mean
	Puddled	Non puddled	
Control	0.62	0.57	0.60
100% NPK	0.70	0.61	0.65
100% NPK (25% substituted by FYM)	0.81	0.63	0.72
100% NPK + Green manure	0.70	0.62	0.66
100% NPK + Crop residues	0.62	0.55	0.59
100% organic source	0.66	0.60	0.63
Blank plot	0.66	0.57	0.62
Mean	0.68	0.59	

LSD ($P = 0.05$): Fertilizer – 0.033; Puddling - 0.01

Table 23. Organic Carbon (OC) content of rice soil (0-15 cm) at tillering stage in 2002

Fertilizer treatment	Organic carbon (%)		Mean
	Puddled	Non puddled	
Control	0.63	0.56	0.60
100% NPK	0.67	0.60	0.64
100% NPK (25% substituted by FYM)	0.77	0.64	0.70
100% NPK + Green manure	0.72	0.62	0.67
100% NPK + Crop residues	0.66	0.60	0.63
100% organic source	0.64	0.61	0.63
Blank plot	0.64	0.60	0.62
Mean	0.67	0.60	

LSD ($P = 0.05$): Fertilizer – 0.029; Puddling - 0.01

Maximum values of soil organic carbon in 100% NPK and 100% organic source treatments were found to be 0.66% and 0.64% and at flowering stage of the crop (Table 24). Soil organic carbon content in crop residue treatment was maximum (0.65%) during harvesting time of the crop (Table 25). In this crop puddling of soil significantly increased the soil organic carbon content. At 0-15 cm soil depth puddled treatments showed (12-16)% more organic carbon content than non-puddled one while in 15-30 cm soil layer this value is (15-20)%.

In the 15-30 cm soil layer fertilizer did not have any significant effect on organic carbon content except for the sowing stage of the crop (Tables 26-29). At sowing stage organic carbon was maximum (0.38%) in FYM treatment followed by green manure treated plots (0.37%). But soil organic carbon of other treatments did not differ significantly.

Wheat 2002

FYM, green manure and totally organically treated plots showed higher organic carbon content of soil as compared to others at all the growth stages. The maximum value of soil organic carbon was 0.67% in FYM treatment at CRI and flowering stage (Table 30 and 32). Crop residue treatment also showed significantly high amount of organic carbon in soil with the maximum value of 0.63% at the tillering stage (Table 31). As expected, the blank plot recorded less organic carbon than fertilized plots. Soil organic carbon was not affected by the

Table 24. Organic Carbon (OC) content of rice soil (0-15 cm) at flowering stage in 2002

Fertilizer treatment	Organic carbon (%)		Mean
	Puddled	Non puddled	
Control	0.65	0.58	0.62
100% NPK	0.71	0.61	0.66
100% NPK (25% substituted by FYM)	0.78	0.63	0.70
100% NPK + Green manure	0.77	0.61	0.69
100% NPK + Crop residues	0.68	0.60	0.64
100% organic source	0.69	0.62	0.65
Blank plot	0.67	0.60	0.64
Mean	0.71	0.61	

LSD ($P = 0.05$): Fertilizer – 0.027; Puddling - 0.01

Table 25. Organic Carbon (OC) content of rice soil (0-15 cm) after harvesting in 2002

Fertilizer treatment	Organic carbon (%)		Mean
	Puddled	Non puddled	
Control	0.64	0.59	0.62
100% NPK	0.70	0.60	0.65
100% NPK (25% substituted by FYM)	0.75	0.62	0.68
100% NPK + Green manure	0.70	0.60	0.65
100% NPK + Crop residues	0.69	0.62	0.65
100% organic source	0.68	0.61	0.64
Blank plot	0.66	0.58	0.62
Mean	0.69	0.60	

LSD ($P = 0.05$): Fertilizer – 0.027; Puddling - 0.01

Table 26. Organic Carbon (OC) content of rice soil (15-30 cm) at time of sowing in 2002

Fertilizer treatment	Organic carbon (%)		Mean
	Puddled	Non puddled	
Control	0.37	0.32	0.34
100% NPK	0.38	0.35	0.36
100% NPK (25% substituted by FYM)	0.40	0.35	0.38
100% NPK + Green manure	0.38	0.36	0.37
100% NPK + Crop residues	0.41	0.32	0.36
100% organic source	0.40	0.32	0.36
Blank plot	0.36	0.34	0.35
Mean	0.39	0.34	

LSD ($P = 0.05$): Fertilizer – 0.03; Puddling - 0.03

Table 27. Organic Carbon (OC) content of rice soil (15-30 cm) at tillering stage in 2002

Fertilizer treatment	Organic carbon (%)		Mean
	Puddled	Non puddled	
Control	0.37	0.34	0.36
100% NPK	0.39	0.32	0.35
100% NPK (25% substituted by FYM)	0.38	0.34	0.36
100% NPK + Green manure	0.41	0.31	0.36
100% NPK + Crop residues	0.40	0.32	0.36
100% organic source	0.41	0.32	0.36
Blank plot	0.37	0.32	0.34
Mean	0.39	0.32	

LSD ($P = 0.05$): Fertilizer – NS; Puddling - 0.04

Table 28. Organic Carbon (OC) content of rice soil (15-30 cm) at flowering stage in 2002

Fertilizer treatment	Organic carbon (%)		Mean
	Puddled	Non puddled	
Control	0.37	0.32	0.35
100% NPK	0.38	0.33	0.36
100% NPK (25% substituted by FYM)	0.38	0.33	0.36
100% NPK + Green manure	0.40	0.33	0.36
100% NPK + Crop residues	0.36	0.31	0.34
100% organic source	0.37	0.31	0.34
Blank plot	0.39	0.33	0.36
Mean	0.38	0.32	

LSD ($P = 0.05$): Fertilizer – NS; Puddling - 0.03

Table 29. Organic Carbon (OC) content of rice soil (15-30 cm) after harvesting in 2002

Fertilizer treatment	Organic carbon (%)		Mean
	Puddled	Non puddled	
Control	0.38	0.32	0.35
100% NPK	0.40	0.31	0.35
100% NPK (25% substituted by FYM)	0.37	0.32	0.37
100% NPK + Green manure	0.38	0.33	0.36
100% NPK + Crop residues	0.36	0.32	0.34
100% organic source	0.37	0.31	0.34
Blank plot	0.38	0.31	0.34
Mean	0.38	0.32	

LSD ($P = 0.05$): Fertilizer – NS; Puddling - 0.04

Table 31. Organic Carbon (OC) content of wheat soil (0-15 cm) at tillering stage in 2002

Fertilizer treatment	Organic carbon (%)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	0.51	0.59	0.55	0.58	0.62	0.60	0.58
100% NPK	0.67	0.66	0.67	0.63	0.65	0.64	0.63
100% NPK (25% substituted by FYM)	0.64	0.68	0.66	0.68	0.64	0.66	0.66
100% NPK + Green manure	0.59	0.63	0.61	0.65	0.62	0.64	0.64
100% NPK + Crop residues	0.69	0.66	0.68	0.57	0.64	0.61	0.63
100% organic source	0.71	0.63	0.67	0.63	0.63	0.63	0.63
Blank plot	0.63	0.59	0.61	0.56	0.55	0.56	0.58
Mean	0.63	0.63		0.61	0.62		

LSD ($P = 0.05$): Fertilizer – 0.04; Tillage- NS; Puddling- NS

Table 32. Organic Carbon (OC) content of wheat soil (0-15 cm) at flowering stage in 2002

Fertilizer treatment	Organic carbon (%)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	0.57	0.63	0.60	0.61	0.58	0.60	0.60
100% NPK	0.6	0.65	0.63	0.68	0.63	0.66	0.64
100% NPK (25% substituted by FYM)	0.67	0.66	0.67	0.68	0.65	0.67	0.67
100% NPK + Green manure	0.64	0.67	0.66	0.67	0.66	0.67	0.66
100% NPK + Crop residues	0.55	0.59	0.57	0.65	0.57	0.61	0.59
100% organic source	0.65	0.63	0.64	0.65	0.63	0.64	0.64
Blank plot	0.55	0.6	0.58	0.6	0.58	0.59	0.58
Mean	0.60	0.63		0.65	0.61		

LSD ($P = 0.05$): Fertilizer – 0.04; Tillage- NS; Puddling- 0.01

tillage treatment. Similarly, puddling of the previous rice crop had no effect on the soil organic carbon content of the succeeding wheat crop. In this year fertilizer did not play any significant role in affecting the soil organic carbon in the 15-30 cm soil layer.

Application of organic carbon through various organic sources of nutrients was the reason of increased soil organic carbon content. In FYM and green manure treatments 1286 and 972 kg ha⁻¹ carbon was added through FYM and green manure, which resulted in higher organic carbon of soil. Similarly in crop residue treatment, carbon was added in the form of residues of the previous crop, which resulted in higher values of organic carbon. Besides this, organic sources such as FYM, green manure, and biofertilizers decompose slowly which resulted in more organic carbon accumulation in soil. The study also corroborated the findings of Sharma et al., (2001) who also found that FYM, green manure and crop residues increased organic carbon significantly over control followed by NPK treatment.

Several studies earlier also have shown increase in soil organic carbon with inorganic fertilization. Halvorson *et al* (1999), for example, observed increase in SOC with N application. This increase in SOC with fertilizer application reflects the response of crop biomass to added N and the quantity of residue returned to the soil. Rasmussen and Rohde (1988) also reported that nitrogen fertilization in

Table 33. Organic Carbon (OC) content of wheat soil (0-15 cm) at harvesting in 2002

Fertilizer treatment	Organic carbon (%)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	0.49	0.56	0.53	0.59	0.6	0.60	0.56
100% NPK	0.61	0.61	0.61	0.63	0.63	0.63	0.62
100% NPK (25% substituted by FYM)	0.64	0.66	0.65	0.64	0.66	0.65	0.65
100% NPK + Green manure	0.6	0.66	0.63	0.65	0.66	0.66	0.64
100% NPK + Crop residues	0.58	0.62	0.60	0.61	0.6	0.61	0.60
100% organic source	0.64	0.66	0.65	0.61	0.65	0.63	0.64
Blank plot	0.54	0.57	0.56	0.57	0.58	0.58	0.57
Mean	0.59	0.62		0.61	0.63		

LSD ($P = 0.05$): Fertilizer – 0.04; Tillage- NS; Puddling- NS

Table 34. Organic Carbon (OC) content of wheat soil (15-30 cm) at CRI stage in 2002

Fertilizer treatment	Organic carbon (%)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	0.34	0.34	0.34	0.31	0.31	0.31	0.33
100% NPK	0.35	0.32	0.34	0.32	0.29	0.31	0.32
100% NPK (25% substituted by FYM)	0.33	0.34	0.34	0.30	0.32	0.31	0.32
100% NPK + Green manure	0.36	0.32	0.34	0.32	0.25	0.29	0.31
100% NPK + Crop residues	0.33	0.33	0.33	0.34	0.34	0.34	0.34
100% organic source	0.34	0.32	0.33	0.30	0.26	0.28	0.31
Blank plot	0.38	0.30	0.34	0.34	0.29	0.32	0.33
Mean	0.35	0.32		0.32	0.29		

LSD ($P = 0.05$): Fertilizer = 0.03; Tillage- NS; Puddling- NS

Table 35. Organic Carbon (OC) content of wheat soil (15-30 cm) at tillering stage in 2002

Fertilizer treatment	Organic carbon (%)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	0.32	0.31	0.32	0.32	0.29	0.31	0.30
100% NPK	0.34	0.32	0.33	0.29	0.32	0.31	0.32
100% NPK (25% substituted by FYM)	0.35	0.34	0.35	0.30	0.34	0.32	0.32
100% NPK + Green manure	0.32	0.33	0.33	0.30	0.32	0.31	0.31
100% NPK + Crop residues	0.32	0.30	0.31	0.29	0.31	0.30	0.28
100% organic source	0.33	0.32	0.33	0.32	0.35	0.34	0.32
Blank plot	0.33	0.33	0.33	0.28	0.30	0.29	0.30
Mean	0.33	0.32		0.30	0.32		

LSD ($P = 0.05$): Fertilizer – NS; Tillage- NS; Puddling- 0.01

Table 36. Organic Carbon (OC) content of wheat soil (15-30 cm) at flowering stage in 2002

Fertilizer treatment	Organic carbon (%)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	0.33	0.34	0.34	0.35	0.32	0.34	0.34
100% NPK	0.37	0.34	0.36	0.30	0.31	0.31	0.33
100% NPK (25% substituted by FYM)	0.34	0.33	0.34	0.31	0.29	0.30	0.32
100% NPK + Green manure	0.34	0.32	0.33	0.30	0.33	0.32	0.32
100% NPK + Crop residues	0.34	0.30	0.32	0.32	0.30	0.31	0.32
100% organic source	0.32	0.32	0.32	0.34	0.31	0.33	0.32
Blank plot	0.34	0.31	0.33	0.33	0.29	0.31	0.32
Mean	0.34	0.32		0.32	0.31		

LSD ($P = 0.05$): Fertilizer – NS; Tillage- NS; Puddling- 0.01

Table 37. Organic Carbon (OC) content of wheat soil (15-30 cm) at harvesting in 2002

Fertilizer treatment	Organic carbon (%)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	0.32	0.34	0.33	0.33	0.34	0.34	0.33
100% NPK	0.35	0.31	0.33	0.31	0.33	0.32	0.33
100% NPK (25% substituted by FYM)	0.35	0.31	0.33	0.31	0.30	0.31	0.32
100% NPK + Green manure	0.37	0.33	0.35	0.33	0.33	0.33	0.34
100% NPK + Crop residues	0.33	0.34	0.34	0.31	0.33	0.32	0.33
100% organic source	0.35	0.34	0.35	0.33	0.32	0.33	0.34
Blank plot	0.36	0.33	0.35	0.31	0.30	0.31	0.33
Mean	0.35	0.33		0.32	0.32		

LSD ($P = 0.05$): Fertilizer – NS; Tillage- NS; Puddling- 0.01

winter wheat crop increases the soil organic carbon. Earlier experiments conducted in India on the rice-wheat cropping system showed that the incorporation of crop residues compared with their removal increased soil organic carbon contents (Singh *et al.*, 2000). High values of soil organic carbon in puddled site may be due to slower decomposition of organic matter in puddled soils under anaerobic conditions which reduced the loss of carbon as CO₂ and higher organic carbon accumulation. Blank plot did not show any change in soil organic carbon content since they had no crop and no fertilizers were applied.

Trends of soil organic carbon in rice-wheat cropping system 2001-2003

In the rice-wheat-rice cropping sequence there was no marked change in organic carbon (%) in both 0-15 and 15-30 cm soil layers over the years. Organic carbon (%) was found to be least in control plot where no fertilizer was added while it was highest in FYM followed by green manure applied treatments. In both puddled- tilled and puddled-notilled site organic carbon of 0-15 cm soil layer increased after 300 days after transplanting and high values were observed during 364-475 days after transplanting (Fig 1a and 2a). This rise was clearly evident in FYM and green manure treatments. This indicates that organic carbon content of surface soil slightly increased during the growth of the second rice crop. The maximum value was 0.81% in FYM treatment. Thus, our experiment shows that in two years of rice-wheat cultivation there is no significant decrease in organic

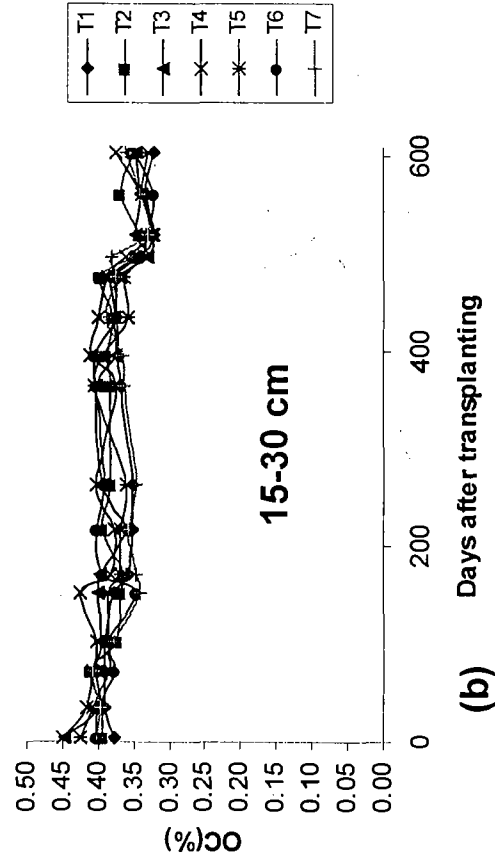
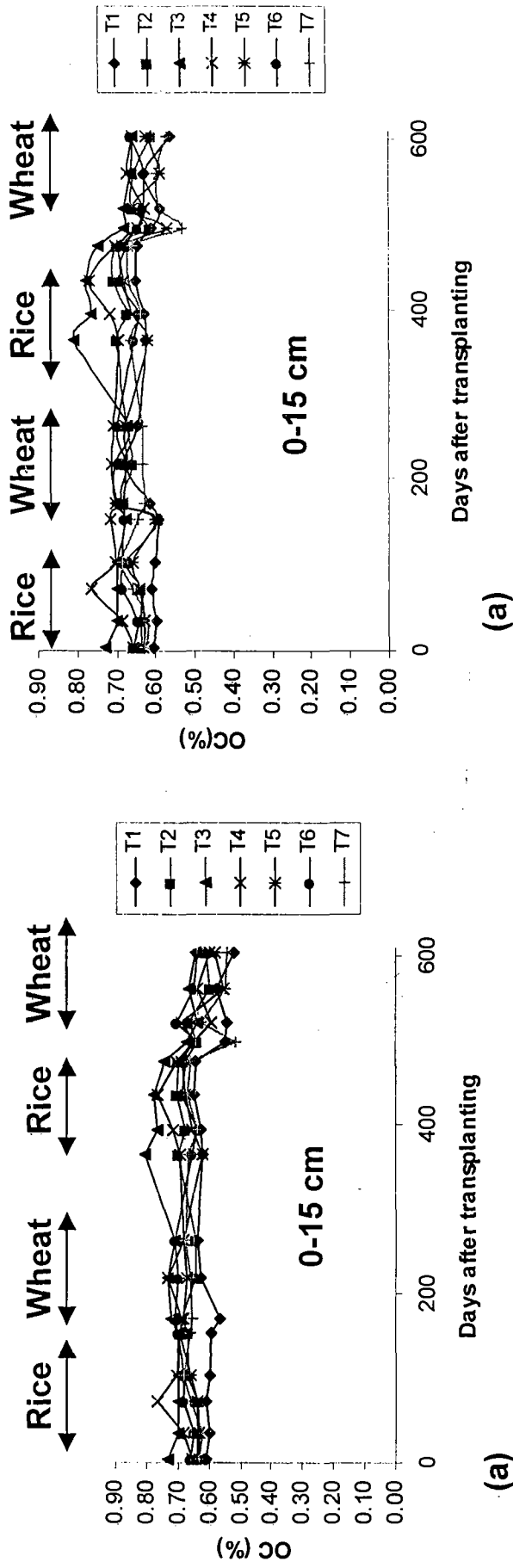


Fig. 1 Organic carbon (%) of puddled tilled soil

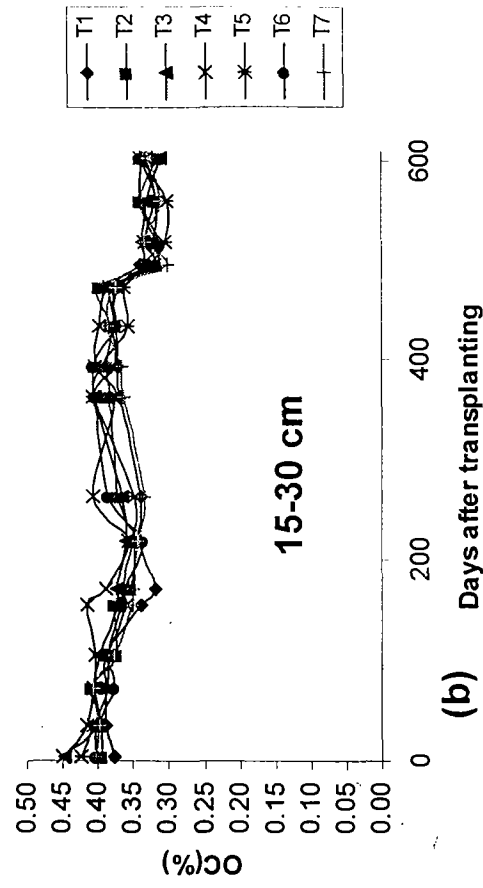
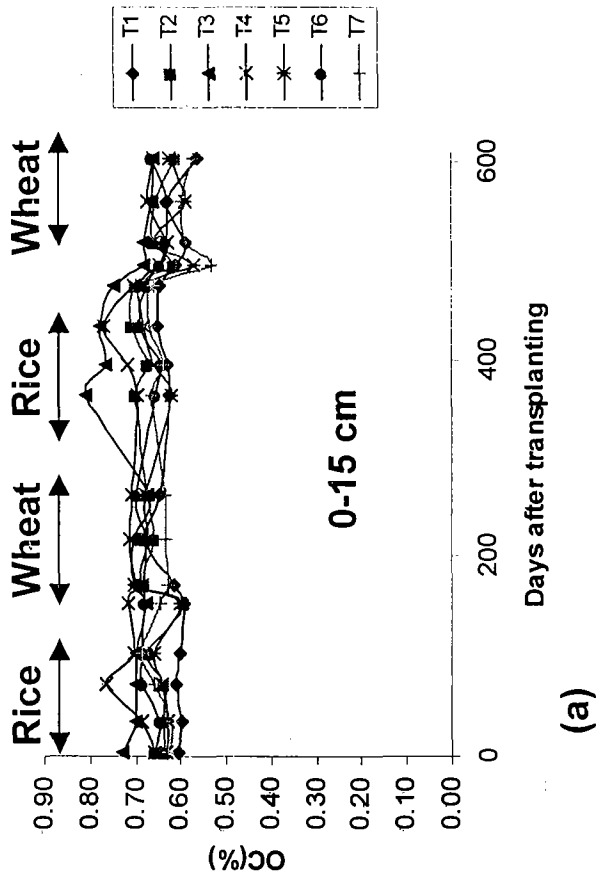


Fig. 2 Organic carbon (%) of puddled notilled soil

T1- Control, T2-100%NPK, T3-NPK+FYM, T4-NPK+GM, T5-NPK+residues, T6-100% organic, T7- Blank plot

carbon in the soil. On the contrary, when fertilized by either inorganic or organic fertilizer there is a slight increase. Ram (2000), however, showed that continuous rice-wheat cultivation for 20 years resulted in decrease in organic carbon from 1.48% to 0.49% and 0.84% in unfertilized and recommended NPK treatment. Such sharp decreases are perhaps possible only when initial organic matter is very high such as in the case of Pantnagar (Aggarwal et al., 2000). In soils where SOC is low as in Delhi environments, there is no significant decrease, even in long-term (Rekhi et al., 2000). Blank plot recorded less organic carbon content, which is somewhat similar to that of control plot. Since no crop was grown in this plot it had no crop residues or roots left in the field, which led to lower carbon content. In non-puddled soil with tillage treatment organic carbon was found to be maximum (0.76%) at 292 days after transplanting (Fig 3a) in FYM treatment. This coincides with the harvesting of the first wheat crop. In this soil organic carbon increased during the growth of the first wheat crop, then it slightly decreased and again it showed increasing trend during the second wheat crop. Similar trend was also observed in non-puddled notilled soil. But in this case maximum value was 0.69% at 259 days after transplanting in both green manure and 100% organic source treatments (Fig 4a). In non-puddled soils both in tillage and notillage treatments organic carbon of 0-15 cm soil slightly increased than the initial value. Organic carbon content of 15-30 cm soil layer also showed decreasing trend in both

puddled and non-puddled soil with tillage and notillage treatments (Fig. 1b, 2b, 3b and 4b).

Dynamics of soil microbial biomass carbon (MBC)

Rice 2001

Microbial biomass carbon of soil was significantly affected by fertilizer and tillage treatments in 0-15 cm soil layer this year (Tables 38-40). Blank plot recorded significantly less microbial biomass carbon than fertilized plots. Similar to organic carbon, microbial biomass carbon was also found to be maximum in FYM and green manure treated plots in both puddled and non puddled soils. Maximum value was recorded in green manure treatment (183.4 mg kg^{-1}) at flowering stage followed by FYM (177.6 mg kg^{-1}) at the time of sowing (Table 40 and 38). At tillering stage green manure treatment showed highest microbial biomass carbon (175.3 mg kg^{-1}) followed by FYM treatment (174.1 mg kg^{-1}) (Table 39). But 100% NPK and crop residue application have not affected soil microbial biomass carbon in any of the crop growth stages. In puddled soil application of FYM and green manure has led to 9% and 17% higher microbial biomass carbon as compared to 100% NPK treatment, respectively which is not the case in non-puddled one.

In non-puddled soils microbial biomass carbon was found to be maximum in green manure treated plots at during flowering stage of the crop (183.4 mg kg^{-1}) (Table 40). Microbial biomass carbon at 0-15 cm soil layer was found to increase gradually

Table 38. Microbial Biomass Carbon (MBC) of rice soil (0-15 cm) at time of sowing in 2001

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)		Mean
	Puddled	Nonpuddled	
Control	159.7	136.6	148.2
100% NPK	170.1	143.5	156.8
100% NPK (25% substituted by FYM)	202.4	152.7	177.6
100% NPK + Green manure	177	157.4	167.2
100% NPK + Crop residues	168.9	128.5	148.7
100% organic source	178.1	151.6	164.9
Blank plot	167.8	133.1	150.5
Mean	174.9	143.3	

LSD ($P = 0.05$): Fertilizer - 12.43; Puddling - 10.72

Table 39. Microbial Biomass Carbon (MBC) of rice soil (0-15 cm) at tillering stage in 2001

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)		Mean
	Puddled	Nonpuddled	
Control	156.2	128.5	142.3
100% NPK	170.1	136.6	153.3
100% NPK (25% substituted by FYM)	190.9	157.4	174.1
100% NPK + Green manure	186.2	164.3	175.3
100% NPK + Crop residues	167.8	131.9	149.8
100% organic source	173.5	155.0	164.3
Blank plot	164.3	142.3	153.3
Mean	172.7	145.1	

LSD ($P = 0.05$): Fertilizer - 17.12; Puddling - 19.11

Table 40. Microbial Biomass Carbon (MBC) of rice soil (0-15 cm) at flowering stage in 2001

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)		Mean
	Puddled	Nonpuddled	
Control	160.8	130.8	145.8
100% NPK	170.1	143.5	156.8
100% NPK (25% substituted by FYM)	190.9	151.6	171.2
100% NPK + Green manure	214.0	152.7	183.4
100% NPK + Crop residues	171.2	140.0	155.6
100% organic source	186.2	142.	164.3
Blank plot	178.2	138.9	158.5
Mean	181.6	142.8	

LSD ($P = 0.05$): Fertilizer - 13.63; Puddling - 4.66

Table 41. Microbial Biomass Carbon (MBC) of rice soil (0-15 cm) after harvesting in 2001

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)		Mean
	Puddled	Nonpuddled	
Control	159.7	136.6	148.2
100% NPK	170.1	143.5	156.8
100% NPK (25% substituted by FYM)	202.4	152.7	177.6
100% NPK + Green manure	177	157.4	167.2
100% NPK + Crop residues	168.9	128.5	148.7
100% organic source	178.1	151.6	164.9
Blank plot	167.8	133.1	150.5
Mean	174.9	143.3	

LSD ($P = 0.05$): Fertilizer - 10.79 Puddling - 14.91

during the plant growth period. It was maximum during the flowering stage. Then again it decreased sharply.

Fertilizer application did not have any significant effect on MBC of 15-30 cm soil layer but puddling significantly increased the microbial biomass carbon of soil in both 0-15 and 15-30 cm soil layers (Tables 42-45). At flowering stage MBC of 0-15 cm soil at puddled site was 181.6 mg kg^{-1} which was 27% higher than nonpuddled soil (Table 40). In 15-30 cm soil layer MBC value during sowing was 84.8 mg kg^{-1} while in nonpuddled soil it is 73.5 mg kg^{-1} (Table 42).

Wheat 2001

Although tillage has not affected the microbial biomass carbon of wheat soil but fertilizer treatments had significant effect on it. Fertilized plots recorded significantly high microbial biomass carbon than control plot (Tables 46-49). Very high values were observed in FYM, green manure and totally organically amended plots. Maximum value was recorded in FYM treatment (201.2 mg kg^{-1}) at flowering stage followed by FYM treatment at tillering stage (200.5 mg kg^{-1}) (Table 48 and 47). In wheat field, crop residues of the previous rice were applied. Plots receiving crop residues showed significant increase in soil microbial biomass carbon as compared to control. But microbial biomass carbon content in these plots was somewhat less than the other treatments. In crop residue applied plots highest MBC (175.6 mg kg^{-1}) was found at flowering stage (Table 48). Similar to rice in wheat also soil microbial

Table 42. Microbial Biomass Carbon (MBC) of rice soil (15-30 cm) at time of sowing in 2001

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)		Mean
	Puddled	Nonpuddled	
Control	66.7	71.2	69.0
100% NPK	74.8	70.3	72.6
100% NPK (25% substituted by FYM)	100.7	74.2	87.5
100% NPK + Green manure	102.3	76.3	89.3
100% NPK + Crop residues	89.4	75.6	82.5
100% organic source	79.7	70.5	75.1
Blank plot	79.7	76.6	78.2
Mean	84.8	73.5	

LSD ($P = 0.05$): Fertilizer – NS; Puddling - 6.96

Table 43. Microbial Biomass Carbon (MBC) of rice soil (15-30 cm) at tillering stage in 2001

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)		Mean
	Puddled	Nonpuddled	
Control	73.2	71.2	72.2
100% NPK	74.8	75.2	75.0
100% NPK (25% substituted by FYM)	78.1	70.5	74.3
100% NPK + Green manure	86.2	74.7	80.5
100% NPK + Crop residues	81.3	78.7	80.0
100% organic source	78.1	67.9	73.0
Blank plot	76.4	82.3	79.4
Mean	78.3	74.4	

LSD ($P = 0.05$): Fertilizer - NS; Puddling - 7.51

Table 44. Microbial Biomass Carbon (MBC) of rice soil (15-30 cm) at flowering stage in 2001

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)		Mean
	Puddled	Nonpuddled	
Control	73.2	77.6	75.4
100% NPK	82.9	80.3	81.6
100% NPK (25% substituted by FYM)	79.7	79.9	79.8
100% NPK + Green manure	81.3	81.2	81.3
100% NPK + Crop residues	71.6	68.7	70.2
100% organic source	66.7	74.3	70.5
Blank plot	81.3	70.1	75.7
Mean	76.7	76.0	

LSD ($P = 0.05$): Fertilizer - NS; Puddling - 10.76

Table 45. Microbial Biomass Carbon (MBC) of rice soil (15-30 cm) after harvesting in 2001

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)		Mean
	Puddled	Nonpuddled	
Control	73.2	74.2	73.7
100% NPK	65.1	73.6	69.4
100% NPK (25% substituted by FYM)	76.4	69.9	73.2
100% NPK + Green manure	79.7	68.4	74.1
100% NPK + Crop residues	71.6	76.2	73.9
100% organic source	71.6	82.4	77.0
Blank plot	66.7	79.5	73.1
Mean	72.0	74.9	

LSD ($P = 0.05$): Fertilizer - NS; Puddling - 8.85

Table 46. Microbial Biomass Carbon (MBC) of wheat soil (0-15 cm) at CRI stage in 2001

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	153.8	158.4	156.1	156.3	163.1	159.7	157.9
100% NPK	168.1	168.6	168.4	172.9	175.0	174.0	171.2
100% NPK (25% substituted by FYM)	202.1	193.7	197.9	187.0	187.6	187.3	192.6
100% NPK + Green manure	181.9	184.6	183.3	189.6	184.3	187.0	185.1
100% NPK + Crop residues	169.9	172.8	171.4	164.4	169.8	167.1	169.2
100% organic source	199.4	183.6	191.5	180.5	179.6	180.1	185.8
Blank plot	162.7	166.1	164.4	165.0	169.9	167.5	165.9
Mean	176.8	175.4		173.7	175.6		

LSD ($P = 0.05$): Fertilizer – 9.83; Tillage- NS; Puddling- NS

Table 47. Microbial Biomass Carbon (MBC) of wheat soil (0-15 cm) at tillering stage in 2001

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	152.3	163.6	158.0	158.2	167.8	163.0	160.5
100% NPK	169.5	172.8	171.2	176.4	183.0	179.7	175.4
100% NPK (25% substituted by FYM)	212.4	205.9	209.2	187.4	196.3	191.9	200.5
100% NPK + Green manure	180.7	189.4	185.1	194.2	186.5	190.4	187.7
100% NPK + Crop residues	164.2	172.1	168.2	170.9	170.0	170.5	169.3
100% organic source	203.6	183.8	193.7	184.1	181.9	183.0	188.4
Blank plot	164.2	165.1	164.7	166.1	171.9	169.0	166.8
Mean	178.1	179.0		176.8	179.6		

LSD ($P = 0.05$): Fertilizer – 7.19; Tillage- NS; Puddling- NS

Table 48. Microbial Biomass Carbon (MBC) of wheat soil (0-15 cm) at flowering stage in 2001

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	156.9	165.6	161.3	159.1	175.1	167.1	164.2
100% NPK	175.2	177.7	176.5	176.3	184.0	180.2	178.3
100% NPK (25% substituted by FYM)	208.6	208.9	208.8	186.9	200.3	193.6	201.2
100% NPK + Green manure	192.5	192.6	192.6	194.1	190.0	192.1	192.3
100% NPK + Crop residues	174.1	178.0	176.1	171.5	178.7	175.1	175.6
100% organic source	201.3	188.9	195.1	189.6	176.7	183.2	189.1
Blank plot	167.2	170.6	168.9	168.6	173.3	171.0	169.9
Mean	182.3	183.2		178.0	182.6		

LSD ($P = 0.05$): Fertilizer – 5.99; Tillage- NS; Puddling- NS

Table 49. Microbial Biomass Carbon (MBC) of wheat soil (0-15 cm) at harvesting in 2001

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	150.8	162.2	156.5	158.4	161.7	160.1	158.3
100% NPK	179.6	170.6	175.1	172.5	174.2	173.4	174.2
100% NPK (25% substituted by FYM)	177.9	185.2	181.6	173.8	186.4	180.1	180.8
100% NPK + Green manure	182.9	178.5	180.7	180.0	178.6	179.3	180.0
100% NPK + Crop residues	166.3	167.3	166.8	169.5	168.9	169.2	168.0
100% organic source	170.3	171.6	171.0	174.2	175.3	174.8	172.9
Blank plot	155.1	166.6	160.9	163.0	166.1	164.6	162.7
Mean	169.0	171.7		170.2	173.0		

LSD ($P = 0.05$): Fertilizer – 5.07; Tillage- NS; Puddling- NS

biomass carbon was found to be maximum at flowering stage. The MBC content increased upto flowering stage and then showed decreasing trend.

In the second soil layer (15-30) cm microbial biomass carbon was not at all affected by the fertilizer treatments (Tables 50-53). Maximum value was recorded (85.5 mg kg^{-1}) in FYM treatment at tillering stage (Table 51). Tillage significantly affected the soil microbial biomass carbon of 15-30 cm soil layer in the first rice crop at sowing and flowering stage. At both the stages puddled soils with tillage treatment showed significantly higher microbial biomass carbon as compared to others. Puddled tilled soil recorded maximum soil MBC (86 mg kg^{-1}) at flowering stage of the crop (Table 52). Non-puddled tilled soil showed highest values of soil MBC (81.3 mg kg^{-1}) at tillering stage (Table 51). At the flowering stage puddled tilled soils were found to have 18% more microbial biomass carbon than puddled notilled soils while non-puddled tilled soils had 3.5% more microbial biomass carbon than non-puddled notilled soil.

Rice 2002

In this year also microbial biomass carbon content was higher in organically amended plots (Tables 54-57). Fertilizer played significant role in enhancing the microbial biomass carbon content of both the soil layers. In most cases blank plot recorded significantly less microbial biomass carbon than the fertilized plots. At 0-15 cm soil layer maximum microbial biomass carbon was observed in FYM treatment in

Table 50. Microbial Biomass Carbon (MBC) of wheat soil (15-30 cm) at CRI stage in 2001

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	81.1	78.7	79.9	78.0	71.5	74.8	77.3
100% NPK	72.0	77.1	74.6	74.6	74.7	74.7	74.6
100% NPK (25% substituted by FYM)	87.9	87.5	87.7	79.4	80.4	79.9	83.8
100% NPK + Green manure	84.7	78.9	81.8	81.8	82.2	82.0	81.9
100% NPK + Crop residues	86.0	74.0	80.0	79.0	73.7	76.4	78.2
100% organic source	85.0	82.3	83.7	81.2	79.5	80.4	82.0
Blank plot	79.6	76.3	78.0	70.6	76.3	73.5	75.7
Mean	82.3	79.3		77.8	76.9		

LSD ($P = 0.05$): Fertilizer – NS; Tillage- 1.89; Puddling- NS

Table 51. Microbial Biomass Carbon (MBC) of wheat soil (15-30 cm) at tillering stage in 2001

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	74.8	78.8	76.8	84.9	78.0	81.5	79.1
100% NPK	77.2	69.8	73.5	70.3	81.7	76.0	74.8
100% NPK (25% substituted by FYM)	94.1	85.6	89.9	77.1	85.1	81.1	85.5
100% NPK + Green manure	75.8	86.7	81.3	89.7	71.0	80.4	80.8
100% NPK + Crop residues	88.0	75.9	82.0	86.3	80.3	83.3	82.6
100% organic source	92.4	71.3	81.9	85.3	75.8	80.6	81.2
Blank plot	79.0	78.8	78.9	75.6	75.5	75.6	77.2
Mean	83.0	78.1		81.3	78.2		

LSD ($P = 0.05$): Fertilizer – NS; Tillage- NS; Puddling- NS

Table 52. Microbial Biomass Carbon (MBC) of wheat soil (15-30 cm) at flowering stage in 2001

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	73.7	74.1	73.9	85.2	71.6	78.4	76.2
100% NPK	83.5	84.7	84.1	79.5	79.1	79.3	81.7
100% NPK (25% substituted by FYM)	98.7	80.7	89.7	78.7	76.6	77.7	83.7
100% NPK + Green manure	89.9	78.0	84.0	67.8	81.0	74.4	79.2
100% NPK + Crop residues	84.6	63.8	74.2	78.0	75.4	76.7	75.5
100% organic source	79.2	59.3	69.3	92.4	80.2	86.3	77.8
Blank plot	92.4	70.0	81.2	76.0	75.2	75.6	78.4
Mean	86.0	72.9		79.7	77.0		

LSD ($P = 0.05$): Fertilizer – NS; Tillage- 6.79; Puddling- NS

Table 53. Microbial Biomass Carbon (MBC) of wheat soil (15-30 cm) at harvesting in 2001

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	73.7	70.4	72.1	74.0	71.6	72.8	72.4
100% NPK	74.0	71.8	72.9	73.1	79.1	76.1	74.5
100% NPK (25% substituted by FYM)	80.5	79.0	79.8	74.2	76.6	75.4	77.6
100% NPK + Green manure	78.5	81.8	80.2	81.1	81.0	81.1	80.6
100% NPK + Crop residues	76.4	75.0	75.7	76.7	75.4	76.1	75.9
100% organic source (50% FYM + 25% Biofertilizer + 25% Green manure)	73.7	74.1	73.9	69.2	80.2	74.7	74.3
Blank plot	71.7	73.8	72.8	68.4	75.2	71.8	72.3
Mean	75.5	75.1		73.8	77.0		

LSD ($P = 0.05$): Fertilizer – 4.5; Tillage- NS; Puddling- NS

Table 54. Microbial Biomass Carbon (MBC) of rice soil (0-15 cm) at time of sowing in 2002

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)		Mean
	Puddled	Nonpuddled	
Control	158.4	145.8	152.1
100% NPK	179.8	175.8	177.8
100% NPK (25% substituted by FYM)	211.9	195.9	203.9
100% NPK + Green manure	201.4	176.3	188.9
100% NPK + Crop residues	175.9	172.2	174.1
100% organic source	181.6	156.6	169.1
Blank plot	164.2	166.3	165.3
Mean	181.9	169.8	
LSD ($P = 0.05$): Fertilizer - 16.23; Puddling - 2.01			

Table 55. Microbial Biomass Carbon (MBC) of rice soil (0-15 cm) at tillering stage in 2002

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)		Mean
	Puddled	Nonpuddled	
Control	157.2	164.6	160.9
100% NPK	180.2	173.7	177.0
100% NPK (25% substituted by FYM)	218.3	201.5	209.9
100% NPK + Green manure	194.0	185.5	189.8
100% NPK + Crop residues	177.1	168.7	172.9
100% organic source	207.4	172.9	190.2
Blank plot	161.9	166.4	164.2
Mean	185.2	176.2	
LSD ($P = 0.05$): Fertilizer - 9.06; Puddling - 3.04			

Table 56. Microbial Biomass Carbon (MBC) of rice soil (0-15 cm) at flowering stage in 2002

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)		Mean
	Puddled	Non puddled	
Control	161.7	168.2	165.0
100% NPK	194.2	182.3	188.3
100% NPK (25% substituted by FYM)	232.6	215.6	224.1
100% NPK + Green manure	214.3	198.7	206.5
100% NPK + Crop residues	180.3	173.7	177.0
100% organic source	212.3	181.1	196.7
Blank plot	169.2	169.4	169.3
Mean	194.9	184.1	
LSD ($P = 0.05$): Fertilizer - 9.65; Puddling - 2.8			

Table 57. Microbial Biomass Carbon (MBC) of rice soil (0-15 cm) after harvesting in 2002

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)		Mean
	Puddled	Non puddled	
Control	172.0	161.0	166.5
100% NPK	182.1	171.3	176.7
100% NPK (25% substituted by FYM)	212.1	180.9	196.5
100% NPK + Green manure	206.1	168.1	187.1
100% NPK + Crop residues	172.4	174.5	173.5
100% organic source	180.8	166.2	173.5
Blank plot	164.4	162.3	163.4
Mean	184.3	169.2	
LSD ($P = 0.05$): Fertilizer - 14.64; Puddling - NS			

flowering stage at both puddled (232.6 mg kg^{-1}) and non-puddled (215.6 mg kg^{-1}) site (Table 56). 100% NPK treatment also showed significantly high amount of microbial biomass carbon than control and maximum value (188.3 mg kg^{-1}) was observed at flowering stage (Table 56). Crop residue treatment had higher microbial biomass carbon content and the maximum value was observed at flowering stage (177 mg kg^{-1}). Soil MBC was higher in puddle site and the highest value was recorded (194.9 mg kg^{-1}) at flowering stage of the crop (Table 56).

In 15-30 cm soil layer blank plot recorded least microbial biomass carbon content followed by control (Tables 58-61). Microbial biomass carbon of this soil layer was significantly increased by fertilizer and organic matter application. Green manure treatment recorded maximum MBC (97.0 mg kg^{-1}) during sowing time of the crop (Table 59). Puddled soil showed significantly more microbial biomass carbon than non-puddled soil in this layer and the maximum value (95.1 mg kg^{-1}) was observed during sowing of the rice crop (Table 58). During the crop growth period highest values of microbial biomass carbon were obtained at flowering stage.

Wheat 2002

Fertilizer application significantly increased soil microbial biomass carbon (Tables 62-65). At the time of sowing and at tillering stage blank plot recorded significantly high amount of soil MBC than control. In FYM treatment microbial biomass carbon was found to be maximum (190 mg kg^{-1}) at tillering and flowering stage of the crop

Table 58. Microbial Biomass Carbon (MBC) of rice soil (15-30 cm) at time of sowing in 2002

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)		Mean
	Puddled	Non puddled	
Control	93.1	88.3	90.7
100% NPK	95.6	87.5	91.6
100% NPK (25% substituted by FYM)	98.7	89.5	94.1
100% NPK + Green manure	96.2	97.8	97.0
100% NPK + Crop residues	95.4	92.1	93.8
100% organic source	96.1	79.3	87.7
Blank plot	90.3	78.6	84.5
Mean	95.1	87.6	

LSD ($P = 0.05$): Fertilizer - 5.21; Puddling - 5.4

Table 59. Microbial Biomass Carbon (MBC) of rice soil (15-30 cm) at tillering stage in 2002

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)		Mean
	Puddled	Nonpuddled	
Control	97.3	90.6	94.0
100% NPK	98.7	88.4	93.6
100% NPK (25% substituted by FYM)	93.8	83.0	88.4
100% NPK + Green manure	88.4	94.2	91.3
100% NPK + Crop residues	72.9	87.2	80.1
100% organic source	98.5	79.5	89.0
Blank plot	88.8	85.2	87.0
Mean	91.2	86.9	

LSD ($P = 0.05$): Fertilizer - 4.5; Puddling - NS

Table 60. Microbial Biomass Carbon (MBC) of rice soil (15-30 cm) at flowering stage in 2002

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)		Mean
	Puddled	Non puddled	
Control	95.4	78.7	87.1
100% NPK	96.3	95.5	95.9
100% NPK (25% substituted by FYM)	93.3	92.3	92.8
100% NPK + Green manure	97.2	76.3	86.8
100% NPK + Crop residues	84.1	82.4	83.3
100% organic source	89.7	84.5	87.1
Blank plot	82.0	74.8	78.4
Mean	91.1	83.5	

LSD ($P = 0.05$): Fertilizer - 6.57; Puddling - 3.45

Table 61. Microbial Biomass Carbon (MBC) of rice soil (15-30 cm) after harvesting in 2002

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)		Mean
	Puddled	Non puddled	
Control	78.4	88.3	83.4
100% NPK	91.8	73.1	82.5
100% NPK (25% substituted by FYM)	99.2	86.9	93.1
100% NPK + Green manure	93.4	71.8	82.6
100% NPK + Crop residues	90.8	77.0	83.9
100% organic source	87.4	71.0	79.2
Blank plot	86.1	84.7	85.4
Mean	89.6	79.0	

LSD ($P = 0.05$): Fertilizer - 11.41; Puddling - NS

Table 62. Microbial Biomass Carbon (MBC) of wheat soil (0-15 cm) at CRI stage in 2002

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	147.1	159.1	153.1	148.7	155.6	152.2	152.6
100% NPK	167.5	170.9	169.2	175.1	171.2	173.2	171.2
100% NPK (25% substituted by FYM)	184.6	187.1	185.9	185.1	180.0	182.6	184.2
100% NPK + Green manure	179.7	184.8	182.3	188.3	173.6	181.0	181.6
100% NPK + Crop residues	166.2	171.2	168.7	162.2	164.1	163.2	165.9
100% organic source	183.9	183.7	183.8	176.7	181.4	179.1	181.4
Blank plot	158.7	163.3	161.0	156.1	158.8	157.5	159.2
Mean	169.7	174.3		170.3	169.2		

LSD ($P = 0.05$): Fertilizer – 6.1; Tillage- NS; Puddling- NS

Table 63. Microbial Biomass Carbon (MBC) of wheat soil (0-15 cm) at tillering stage in 2002

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	149.6	162.4	156.0	145.9	158.7	152.3	154.2
100% NPK	173.0	174.9	174.0	168.0	175.0	171.5	172.7
100% NPK (25% substituted by FYM)	190.1	193.4	191.8	189.5	186.8	188.2	190.0
100% NPK + Green manure	189.2	188.4	188.8	183.3	183.2	183.3	186.0
100% NPK + Crop residues	165.9	172.7	169.3	163.3	166.1	164.7	167.0
100% organic source	194.8	187.9	191.4	189.2	185.9	187.6	189.5
Blank plot	155.7	164.5	160.1	162.1	164.1	163.1	161.6
Mean	174.1	177.7		171.6	174.3		

LSD ($P = 0.05$): Fertilizer – 6.9; Tillage- 2.7; Puddling- NS

Table 64. Microbial Biomass Carbon (MBC) of wheat soil (0-15 cm) at flowering stage in 2002

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	155.4	163.8	159.6	154.2	158.1	156.2	157.9
100% NPK	172.0	176.9	174.5	171.7	172.9	172.3	173.4
100% NPK (25% substituted by FYM)	190.0	193.7	191.9	189.2	187.1	188.2	190.0
100% NPK + Green manure	190.8	186.1	188.5	182.2	183.6	182.9	185.7
100% NPK + Crop residues	168.7	174.5	171.6	165.3	163.5	164.4	168.0
100% organic source	192.6	190.3	191.5	190.6	177.9	184.3	187.9
Blank plot	152.6	165.0	158.8	154.1	156.0	155.1	156.9
Mean	174.6	178.6		172.5	171.3		

LSD ($P = 0.05$): Fertilizer – 6.4; Tillage- NS; Puddling- NS

Table 65. Microbial Biomass Carbon (MBC) of wheat soil (0-15 cm) at harvesting in 2002

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	151.0	150.6	150.8	147.5	152.3	149.9	150.4
100% NPK	161.1	167.8	164.5	157.9	168.5	163.2	163.8
100% NPK (25% substituted by FYM)	178.1	174.0	176.1	173.9	170.2	172.1	174.1
100% NPK + Green manure	169.0	170.1	169.6	173.9	165.0	169.5	169.5
100% NPK + Crop residues	160.6	163.6	162.1	158.6	156.6	157.6	159.9
100% organic source	174.8	176.2	175.5	170.7	170.7	170.7	173.1
Blank plot	144.5	155.1	149.8	143.9	150.6	147.3	148.5
Mean	162.7	165.3		160.9	162.0		

LSD ($P = 0.05$): Fertilizer – 5.9; Tillage- NS; Puddling- 2.5

(Table 63 and 64). Similar to the previous wheat crop microbial biomass carbon was significantly high in crop residue treatment and the highest value (168 mg kg^{-1}) was observed at flowering stage (Table 64). Maximum soil microbial biomass carbon (189.5 mg kg^{-1}) in organically treated plots was observed at tillering stage (Table 63). In this year also microbial biomass carbon showed similar trend, at different growth stages as that of the previous wheat crop. Tillage significantly affected soil MBC only at tillering stage. At this stage puddled tilled soils recorded 2% more microbial biomass carbon than puddled notilled soil.

Microbial biomass carbon of 15-30 cm soil layer was not affected by the fertilizer treatments (Tables 66-69). In this wheat crop tillage treatment had no effect on microbial biomass carbon. Similar to organic carbon, microbial biomass carbon of wheat soil was not affected by puddling of soil of the previous rice crop.

Use of organic matter resulted in higher microbial activity leading to increased microbial biomass carbon content of soils. Since biological activity is concentrated near the surface, in the first year microbial biomass carbon of second soil layer (15-30 cm) did not show much change. Similar observations were also made by Gunapala and Scow (1998) who reported significantly higher soil microbial biomass carbon in organic farming systems as compared to conventional ones. Hossain et al., (1995) also observed that fertilizer application has significant effect on microbial biomass carbon of surface soil. According to Gupta *et al.*, (1994)

Table 66. Microbial Biomass Carbon (MBC) of wheat soil (15-30 cm) at CRI stage in 2002

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	73.9	80.1	77.0	71.3	69.9	70.6	73.8
100% NPK	80.2	73.1	76.7	79.5	75.4	77.5	77.1
100% NPK (25% substituted by FYM)	88.3	80.1	84.2	85.2	71.8	78.5	81.4
100% NPK + Green manure	66.4	75.3	70.9	75.4	70.6	73.0	71.9
100% NPK + Crop residues	74.3	73.6	74.0	70.3	75.2	72.8	73.4
100% organic source	71.9	70.2	71.1	72.5	82.7	77.6	74.3
Blank plot	71.6	77.4	74.5	70.5	79.2	74.9	74.7
Mean	75.2	75.7		75.0	75.0		

LSD ($P = 0.05$): Fertilizer – NS; Tillage- NS; Puddling- NS

Table 67. Microbial Biomass Carbon (MBC) of wheat soil (15-30 cm) at tillering stage in 2002

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	80.9	92.4	86.7	70.7	71.1	70.9	78.8
100% NPK	86.3	73.4	79.9	82.5	71.1	76.8	78.3
100% NPK (25% substituted by FYM)	73.8	77.5	75.7	77.3	80.9	79.1	77.4
100% NPK + Green manure	75.1	75.7	75.4	76.9	75.2	76.1	75.7
100% NPK + Crop residues	81.1	70.5	75.8	79.3	84.6	82.0	78.9
100% organic source	76.4	81.3	78.9	74.9	81.6	78.3	78.6
Blank plot	87.1	81.3	84.2	74.3	73.6	74.0	79.1
Mean	80.1	78.9		76.6	76.9		

LSD ($P = 0.05$): Fertilizer – NS; Tillage- NS; Puddling- NS

Table 68. Microbial Biomass Carbon (MBC) of wheat soil (15-30 cm) at flowering stage in 2002

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	71.6	70.0	70.8	78.3	73.7	76.0	73.4
100% NPK	81.5	74.3	77.9	70.2	72.4	71.3	74.6
100% NPK (25% substituted by FYM)	76.5	82.2	79.4	86.6	79.3	83.0	81.2
100% NPK + Green manure	80.6	71.8	76.2	70.6	82.2	76.4	76.3
100% NPK + Crop residues	79.2	75.1	77.2	80.0	84.4	82.2	79.7
100% organic source	77.4	82.9	80.2	76.0	78.4	77.2	78.7
Blank plot	73.5	74.3	73.9	79.3	77.6	78.5	76.2
Mean	77.2	75.8		77.3	78.3		

LSD ($P = 0.05$): Fertilizer – NS; Tillage- NS; Puddling- NS

Table 69. Microbial Biomass Carbon (MBC) of wheat soil (15-30 cm) at harvesting in 2002

Fertilizer treatment	Microbial biomass carbon (mg kg ⁻¹)						Mean
	Puddled			Non puddled			
	Tillage	No tillage	Mean	Tillage	No tillage	Mean	
Control	84.5	72.2	78.4	75.4	79.6	77.5	77.9
100% NPK	75.2	72.1	73.7	78.2	74.6	76.4	75.0
100% NPK (25% substituted by FYM)	71.9	80.7	76.3	82.1	73.3	77.7	77.0
100% NPK + Green manure	75.2	79.5	77.4	73.5	72.8	73.2	75.3
100% NPK + Crop residues	82.1	77.6	79.9	72.3	78.3	75.3	77.6
100% organic source	83.2	81.4	82.3	83.7	72.5	78.1	80.2
Blank plot	81.5	70.5	76.0	80.5	66.7	73.6	74.8
Mean	79.1	76.3		78.0	74.0		

LSD ($P = 0.05$): Fertilizer – NS; Tillage- NS; Puddling- NS

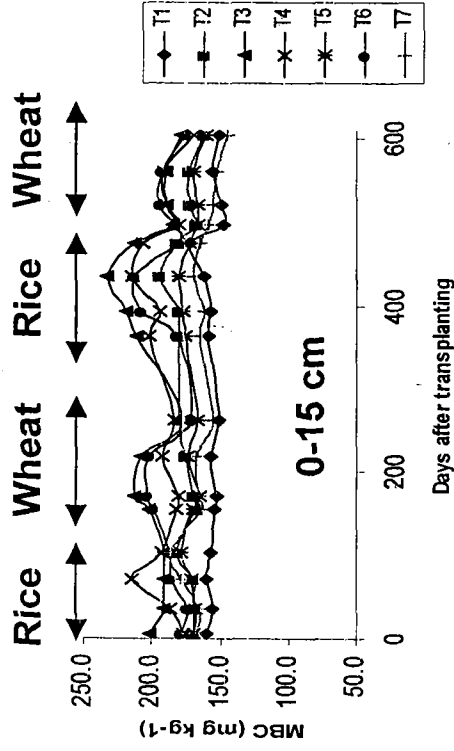
microbial biomass (MB), the living portion of soil organic matter, responds rapidly to changes in soil and crop management practices. They showed that cultivation resulted in smaller increases in MBC at 0-5 cm, but this was offset by larger increases at 5-10 cm depth, particularly in the stubble incorporated treatment. During the crop growing season the microbial activity was probably highest during flowering stage of the crop and therefore microbes tended to assimilate more carbon for their energy requirement. Besides this at flowering stage maximum translocation of nutrients occur from soil to plant. So activity of microbes in rhizosphere is maximum at this stage, which might have caused high values of microbial biomass carbon. The decrease in microbial biomass carbon thereafter may be due to a shift in the composition of the microflora of the soil (Acquaye et al., 2000). Gradual change in total soil organic matter may be difficult to monitor and detect in the short term because of the generally high background carbon levels and natural variability of soils. The living fraction of organic matter, the microbial biomass, rather than total amounts of organic carbon, has been suggested as a useful and more sensitive measure of a change in organic matter status (Powlson *et al.*, 1987). Having a comparatively rapid rate of turnover of 1-2 years (Jenkinson and Ladd, 1981) it is possible to detect changes in this microbial fraction long before they are detectable in the total organic matter and these may even exhibit opposite trends. The microbial biomass C normally comprises 1-5%

of the total soil organic C. However, this percentage, the 'microbial quotient', has been reported to change in a consistent way and to provide a useful indicator of soil processes (Anderson and Domsch, 1989). Higher microbial biomass carbon in puddled soil might be due to the fact that standing water in the puddled rice fields gave rise to anaerobic condition which resulted in greater microbial activity near the root zone and ultimately higher microbial biomass. Application of carbon through crop residue resulted in higher microbial biomass than control but it is less as compared to other fertilizer treatments, which may be due to the fact that crop residues have very high C:N ratio, which slows down the mineralization process. Microbes take longer time to decompose these residues and bring the nutrients in available form. Besides this most of the residues remain in the soil surface where biological activity is less (Stewart, 1993). So microbial biomass carbon content of soil becomes somewhat less in this treatment. Since microbes are mostly active in the rhizosphere so at greater soil depth microbial biomass carbon did not get significantly affected by fertilizer application. Puddling i.e., the repeated tillage of saturated (submerged) soil, has considerable effects on the physical, chemical and biological properties of soil that influences microbial growth. It softens soil, promotes root growth and reduces water and nutrient losses by leaching, thereby increases nutrient and organic carbon availability (Sharma et al., 2003). Availability of organic carbon may also be increased by the mechanical break

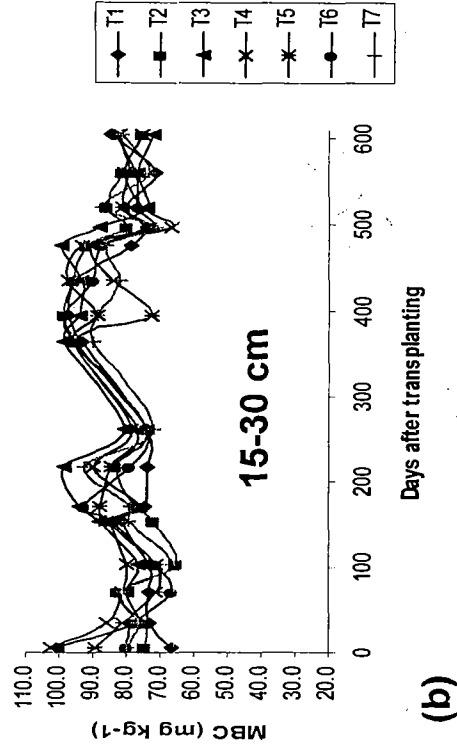
down of organic matter due to repeated tillage of the inundated soil. Puddled and the subsequent submerged condition in rice thus provides a favorable environment for the growth of microbes, particularly soil bacteria (Roger, 1996) resulting in higher MBC in soil. Moreover, spontaneous growth of photodependent free-living blue green algae (BGA) is a basic feature in wetland rice fields (Roger and Watanabe, 1986). The growth of these microbes and the subsequent decomposition of their biomass contribute towards the higher MBC in puddled rice soils compared to the non puddled soils. A favourable temperature in the puddled soil compared to the aerobic soils (Gajri and Majumdar, 2002) may also contribute towards enhanced microbial activity and higher MBC in soil.

Overall trends during rice-wheat cropping 2001-2003

Similar to organic carbon, soil microbial biomass carbon of 0-15 cm soil layer was also found to be higher during the growth of the second rice crop in puddled soil and the maximum value was 232.6 mg kg^{-1} in FYM treatment (Fig. 5a). Two years of rice-wheat cropping resulted in decrease in microbial biomass carbon in both puddled tilled and notilled site. During the first rice crop highest value was seen in green manure applied plots (214 mg kg^{-1}) while in second rice it is in FYM treatment (232.6 mg kg^{-1}). In both the wheat crops microbial biomass carbon was found to be slightly lower in puddled site. But in non-puddled site there was a slight increase in microbial biomass carbon values from the initial one. But highest

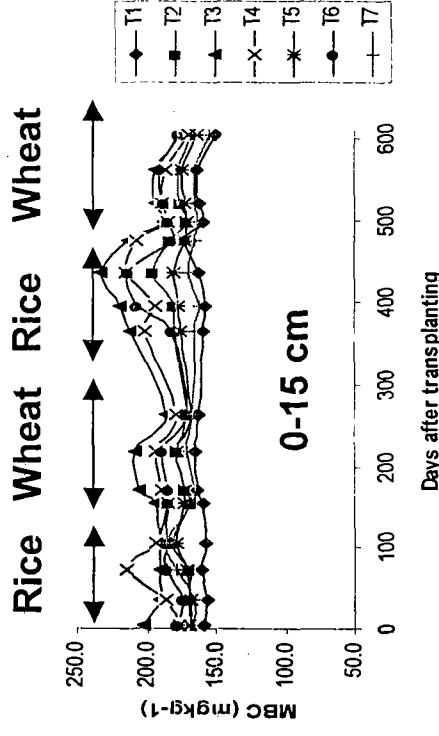


(a)

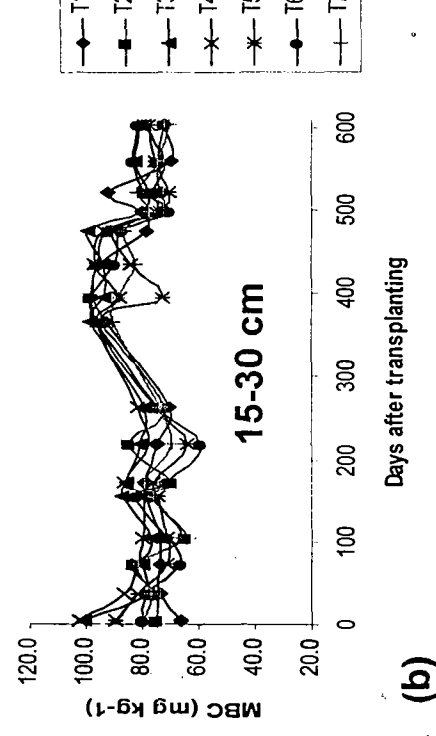


(b)

Fig. 5 Microbial biomass carbon (mg kg^{-1}) of puddled tilled soil



(a)



(b)

Fig. 6 Microbial biomass carbon (mg kg^{-1}) of puddled notilled soil

T1- Control, T2-100%NPK, T3-NPK+FYM, T4-NPK+GM, T5-NPK+GM, T6-100% organic, T7- Blank plot

value (215.6 mg kg^{-1}) was recorded during the second rice crop in FYM treatment (Fig 6a). In non-puddled site initially microbial biomass carbon was much lower than puddled one. After two years of rice-wheat cropping microbial biomass carbon of non puddled soil increased to certain extent but the values were less than puddled soil. Less water application in non-puddled soil might have resulted in slower activity of microbes, which has ultimately lowered the microbial biomass carbon of soil. Numerous studies have reported decrease in microbial biomass due to drying of the soil (Van Gestel *et al.*, 1992). In puddled soils microbial biomass carbon of 15-30 cm soil layer was also found high during second rice crop (364-475 days after transplanting) (Fig. 6b and 7b). In non-puddled soil initially microbial biomass carbon was very low ($36\text{-}57 \text{ mg kg}^{-1}$) in 15-30 cm soil layer but it gradually increased (Table 8). Again after harvesting of the second rice crop the values showed a decreasing trend.

Relationship between soil organic carbon and soil microbial biomass carbon

The relationship between soil organic carbon and microbial biomass carbon recorded throughout the growing period was quantified (Fig. 9). In case of rice the regression equation between the two was:

$$\text{MBC} = 317.14 \text{ SOC} - 27.733$$

Where SOC is soil organic carbon (%) and MBC is microbial biomass carbon (mg kg^{-1}). In case of wheat this relationship (Fig. 10) was:

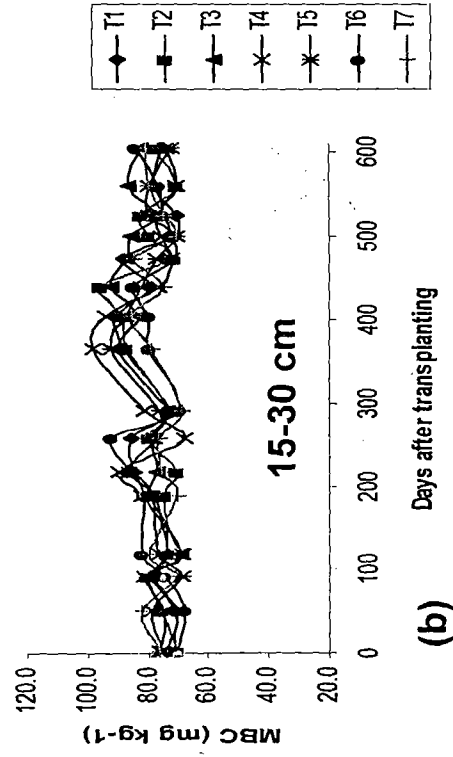
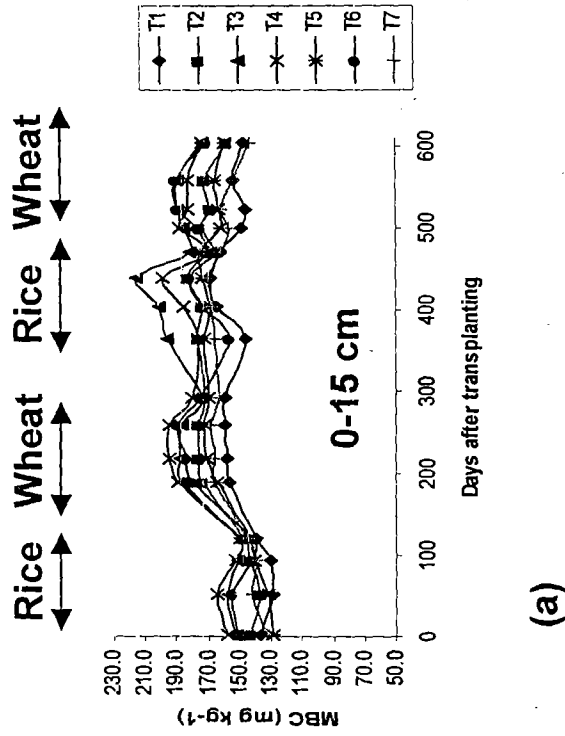


Fig. 7 Microbial biomass carbon (mg kg^{-1}) of nonpuddled tilled soil

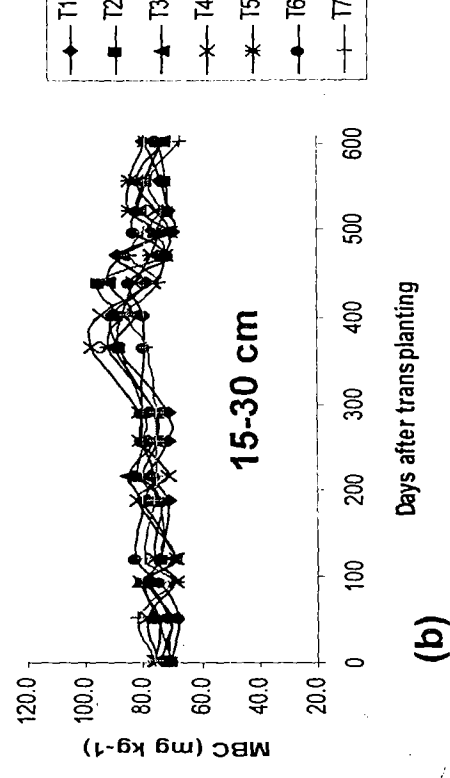
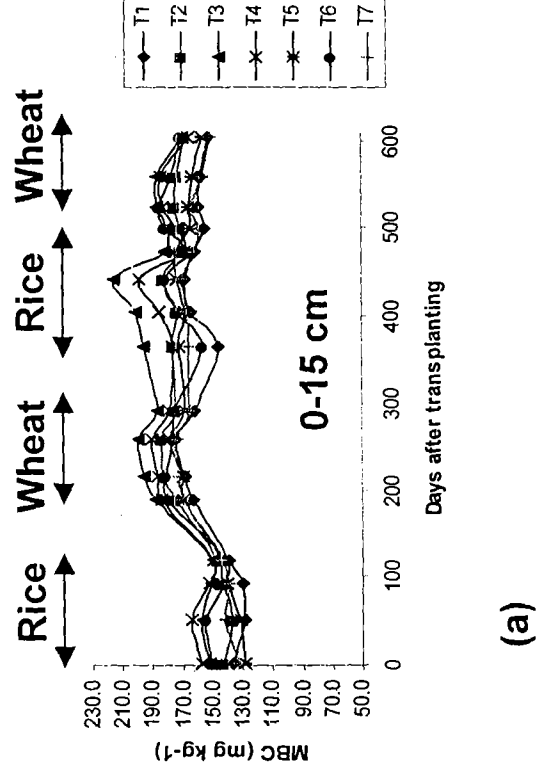


Fig. 8 Microbial biomass carbon (mg kg^{-1}) of nonpuddled notilled soil

T1- Control, T2-100%NPK, T3-NPK+FYM, T4-NPK+GM, T5-NPK+GM, T6-100% organic, T7- Blank plot

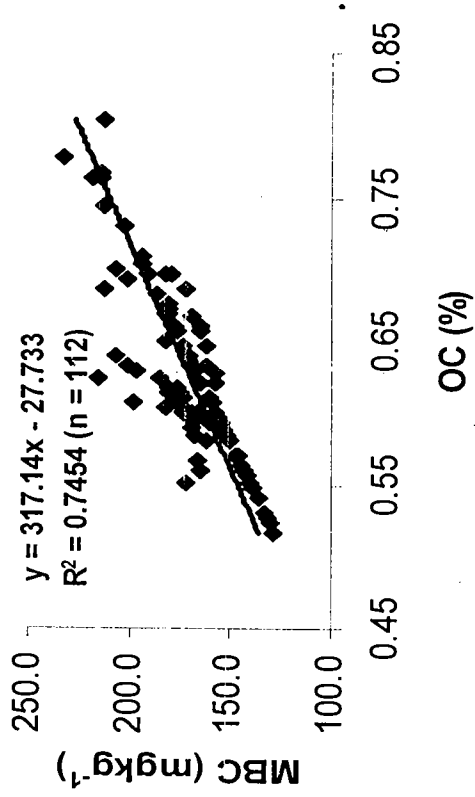


Fig. 9 Relationship between soil organic carbon and soil microbial biomass carbon in rice crop

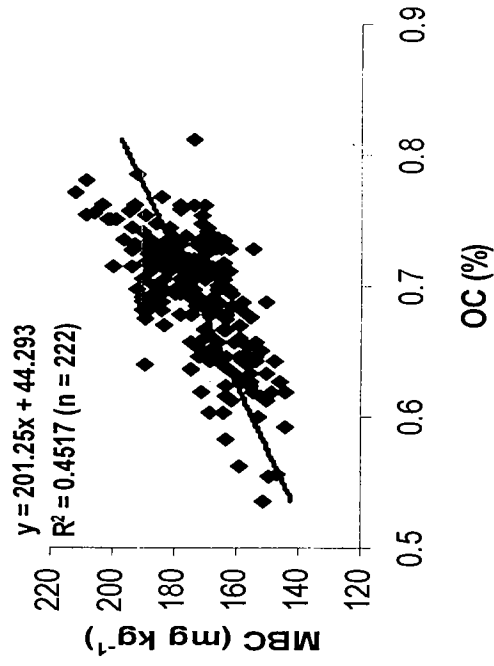


Fig. 10 Relationship between soil organic carbon and soil microbial biomass carbon in wheat crop

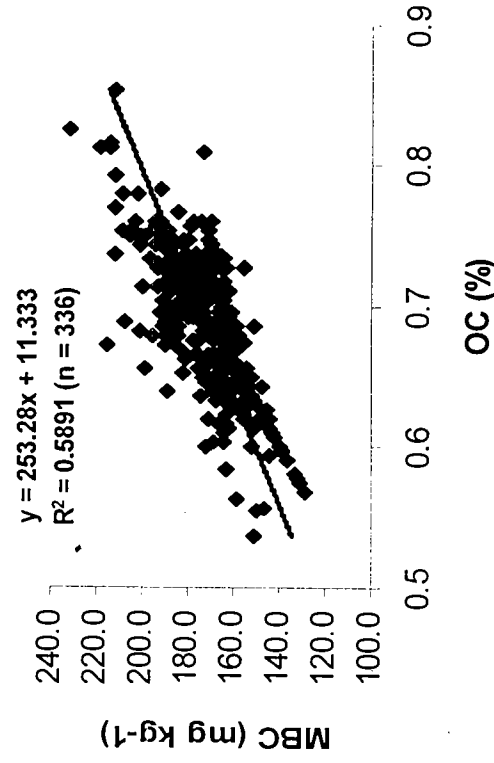


Fig. 11 Relationship between soil organic carbon and soil microbial biomass carbon in rice and wheat crop

$$\text{MBC} = 201.25 \text{ SOC} + 44.293$$

Pooled data for both rice and wheat resulted in the following relationship (Fig. 11):

$$\text{MBC} = 253.28 \text{ SOC} + 11.333$$

That there is a significant linear relationship between MBC and SOC has earlier been shown in temperate environments by several authors (Jenkinson and Ladd, 1981). Our results showed that a similar relationship exists even in tropical environments where the basic SOC levels are very low. Such relationships are, however, likely to be affected by several other factors such as soil type, temperature and pH of the soil. The ratio of soil microbial biomass carbon and soil organic carbon proved to be a reliable soil microbial parameter for describing changes in man made ecosystems. Organic matter is an essential component of soil quality and micro-organisms play a vital role in the maintenance of soil fertility. Thus both organic matter and microbial activity can be regarded as indicators related to the process of soil genesis on minesoils. In agricultural sites this value ranges between 2 and 7% (Azam *et al.*, 1986). Beck (1984) put forward the hypothesis that soils that exhibit a level of bioactivity per unit soil organic carbon higher than an empirical average are “developing” soils with a net accumulation of organic carbon, and those with a lower level are losing organic carbon from a pool of relatively stable humic materials. Gupta *et al.*, (1994) also

observed that that MBC had a significant correlation with the level of total C in the soil in the month of August and October.

Development of InfoCrop model

In order to understand long-term dynamics of carbon in agricultural systems, an extrapolation model can be very useful. Several models such as DNDC, Century, ANIMO have been developed earlier by different authors. Since the code of these models are not available and their preliminary evaluation indicated unsatisfactory performance in Indian environments, a soil carbon dynamics model was developed for the InfoCrop model, developed, calibrated and validated in India. InfoCrop is a generic model to simulate growth, development, water use, nitrogen balance and crop-pest interactions for major annual crops (Aggarwal et al., 2003, unpublished). The model is written in FST language and a Windows based user interface has also been developed. It is user-friendly system that is targeted for increasing applications of crop modelling for a variety of objectives. The primary structure of InfoCrop relating to crop growth and development is based on MACROS (Penning de Vries et al., 1989), WTGROWS (Aggarwal et al., 1994), SUCROS (van Keulen et al., 1997) and ORYZA1 (Kropff et al., 1994). In this model following processes are considered: Phenology, dry matter production, leaf area growth, assimilate partitioning, source-sink balance, nutrient uptake and partitioning, transpiration, water and nutrient stresses and crop-pest interactions.

Each process is described by a set of equations, the parameters of which vary depending upon the crop/cultivar.

In InfoCrop, soil organic matter is divided into two major pools- fresh organic matter (FOM) and humified organic matter (HOM). The HOM is basically soil organic matter in the native soil. Application of any organic matter, e.g. green manure, farmyard manure or crop residue, is added to the FOM pool. The FOM pool is then divided into three sub-pools- carbohydrate, cellulose plus hemicellulose, and lignin.

Apart from the external addition of organic matter like crop residue and green manure, root exudates and dying roots of the standing crop, and root mass of the previous crop are also included in the FOM pool. Amount of root exudates or rhizodeposition has been considered to be linear at $0.6 \text{ mg C g}^{-1} \text{ root day}^{-1}$ up to flowering, after which it is $1.6 \text{ mg C g}^{-1} \text{ root day}^{-1}$ (Mathews et al., 2000). Death of roots has been taken as 2% of existing root dry weight per day. Amount of carbohydrate mineralized is the output for the process. The whole process is considered separately for different soil layers. CA1DEC, amount of carbohydrate mineralized ($\text{kg ha}^{-1} \text{ d}^{-1}$) of a given organic matter 1 is calculated as below.

$$\begin{aligned} \text{CA1DEC} &= \text{OM1CAS} * (1. - \text{EXP} (-\text{DECARB})) * \text{TFAC} * \text{MBFAC} * \text{AMIN1} \\ &\quad (\text{MFAC}, \text{PHFAC}) * \text{AFGEN} (\text{CNMODF}, \text{SOILN1}) \\ \text{OM1CRB} &= (\text{OM1APP} * \text{CARBO1} + (\text{RTDETH} + \text{LASTCP}) * 0.2 + \text{RTEXUD}) * \\ &\quad 0.451 - \text{CA1DEC} \\ \text{OM1CAS} &= \text{INTGRL} (\text{ZERO}, \text{OM1CRB}) \end{aligned}$$

Where OMICRB is the carbohydrate balance in kg ha^{-1} , DECARB, degradation rate of carbohydrate and TFAC, MBFAC, MFAC and PHFAC are correction factors for temperature, microbial biomass, moisture and pH, respectively. OM1AP is the amount of organic matter added (kg ha^{-1}); CARBO1 is the fraction of carbohydrate in OM1AP, RDEATH, mass of dying roots ($\text{kg ha}^{-1} \text{ d}^{-1}$); LASTCP, root mass of the previous crop (kg ha^{-1}); 0.2, fraction of carbohydrate in roots; RTEXUD, root exudates ($\text{kg ha}^{-1} \text{ d}^{-1}$); and CA1DEC, amount of carbohydrate mineralized ($\text{kg ha}^{-1} \text{ d}^{-1}$) and 0.451 is carbon content of carbohydrates.

The effect of microbial activity is dependant on the soil microbial biomass. The relationship described earlier between SOC and MBC (Fig. 11) was used in the model.

The whole process is repeated for different sources of organic matter added. Total decomposition of carbohydrate (CARDEC, $\text{kg ha}^{-1} \text{ d}^{-1}$) is calculated as the summation of CA1DEC, CA2DEC and CA3DEC.

Similarly, degradations of cellulose plus hemicellulose, and lignin of the added organic matter are also calculated.

$$\text{CL1DEC} = \text{OM1CLS} * (1. - \text{EXP} (-\text{DECELL})) * \text{TFAC} * \text{MBFAC} * \text{AMIN1}(\text{MFAC}, \text{PHFAC})$$

$$\text{AMIN1}(\text{MFAC}, \text{PHFAC})$$

$$\text{OM1CLS} = \text{INTGRL} (\text{ZERO}, \text{OM1CEL})$$

$$\text{OM1CEL} = (\text{OM1APP} * \text{CELLU1} + (\text{RTDETH} + \text{LASTCP}) * 0.7) * 0.50 - \text{CL1DEC}$$

where DECELL is the degradation rate of cellulose plus hemicellulose in OM1AP, OM1CEL is the balance of cellulose plus hemicellulose (kg ha^{-1}), CELLU1 is the fraction of cellulose plus hemicellulose in OM1AP; 0.7 is the fraction of cellulose plus hemicellulose in roots; CL1DEC is amount of cellulose plus hemicellulose mineralized ($\text{kg ha}^{-1} \text{ d}^{-1}$) and 0.5 is carbon content of cellulose plus hemicellulose. Total decomposition of cellulose plus hemicellulose (CELDEC, $\text{kg ha}^{-1} \text{ d}^{-1}$) is calculated as the summation of decomposition of different sources of organic matter.

Similar approach was followed in estimating lignin degradation:

$$\text{LI1DEC} = \text{OM1LIS} * (1. - \text{EXP} (-\text{DELIGN})) * \text{TFAC} * \text{MBFAC} * \text{AMIN1}(\text{MFAC}, \text{PHFAC})$$

$$\text{OM1LIS} = \text{INTGRL} (\text{ZERO}, \text{OM1LIG})$$

$$\text{OM1LIG} = (\text{OM1APP} * \text{LIGNI1} + (\text{RTDETH} + \text{LASTCP}) * 0.1) * 0.691 - \text{LI1DEC}$$

where OM1LIG, the balance of lignin (kg ha^{-1}); LIGNI1, fraction of cellulose plus hemicellulose in OM1AP; 0.1, fraction of lignin in roots; LIGMIN, amount of lignin mineralized ($\text{kg ha}^{-1} \text{ d}^{-1}$), DELIGN, degradation rate of lignin and 0.69 is carbon content of lignin. Total decomposition of lignin (LIGDEC, $\text{kg ha}^{-1} \text{ d}^{-1}$) is

calculated as the summation of lignin mineralisation of different sources of organic matter added.

The degradation rate of carbohydrate, cellulose plus hemicellulose and lignin are considered as 0.8, 0.05 and 0.0095 per day, respectively (Saligman and van Keulen, 1981; Mathews et al., 2000).

The degradation of soil organic C pool has been calculated for three different layers using the following equation:

$$\begin{aligned} \text{SOCDC1} &= \text{SOCNT1} * (1 - \text{EXP}(-\text{DESOLC})) * \text{TFAC} * \text{MBFAC} * \\ &\quad \text{AMIN1}(\text{MFAC}, \text{PHFAC}) \\ \text{SOCNT1} &= \text{INTGRL}(\text{SOC1KG}, \text{SOCBL1}) \\ \text{SOC1KG1} &= \text{SOC1} * \text{TKL1} * 220000 * \text{BD1} \text{ to } 3/1.56 \\ \text{SOCBL1} &= -\text{SOCDC1} + \text{CIMMO1} \\ \text{SOCMN1} &= \text{SOCNT1} * (1 - \text{EXP}(-\text{DESOLC})) * \text{TFAC} * \\ &\quad \text{MBFAC} * \text{AMIN1}(\text{MFAC}, \text{PHFAC}) \end{aligned}$$

where SOCDC1 ($\text{kg ha}^{-1} \text{ d}^{-1}$) is the decomposition of soil organic carbon in soil layer 1; DESOLC is the degradation rate of soil organic C, SOC1, TKL1 and BD1 are soil organic carbon content (%), thickness (mm) and bulk density (Mg m^{-3}) of soil in layer 1, 220000 and 1.56 are the coefficients to convert soil organic carbon content from percent to kg ha^{-1} . The soil organic C pool has a much lower turnover rate (0.000085 per day) than the FOM pool.

Net carbon mineralization (CMINTO, kg ha^{-1}) is calculated as the balance between total mineralization from fresh organic matter (carbohydrate, cellulose plus hemicellulose, lignin added through different sources) and soil organic matter, and immobilization of dissolved oxidizable carbon by soil microbes.

$$\text{CMINTO} = \text{CARMIN} + \text{CELMIN} + \text{LIGMIN} + \text{SOCMN1} + \\ \text{SOCMN2} + \text{SOCMN3} - \text{CIMMO1} - \text{CIMMO2} - \text{CIMMO3}$$

CIMMO1 to 3 are the amounts of carbon immobilized by the microbes ($\text{kg ha}^{-1} \text{ d}^{-1}$) in different soil layers and are calculated as follows.

$$\begin{aligned} \text{CIMMO1} &= (\text{CARDEC} + \text{CELDEC} + \text{LIGDEC} + \text{SOCDC1}) \\ &\quad * \text{ASOLC} * \text{TFAC} * \text{MBFAC} * \text{AMIN1}(\text{MFAC}, \text{PHFAC}) \\ \text{CIMMO2} &= \\ &\quad \text{SOCDC2} * \text{ASOLC} * \text{TFAC} * \text{MBFAC} * \text{AMIN1}(\text{MFAC}, \text{PHFAC}) \\ \text{CIMMO3} &= \\ &\quad \text{SOCDC3} * \text{ASOLC} * \text{TFAC} * \text{MBFAC} * \text{AMIN1}(\text{MFAC}, \text{PHFAC}) \end{aligned}$$

where ASOLC is the assimilation rate (per day) of carbon. Other terms in the equations have been described above.

Amount of dissolved organic carbon (DOC, kg ha^{-1}) is then calculated as the balance between total mineralization from fresh organic matter (carbohydrate, cellulose plus hemicellulose, lignin added through different sources) and soil organic matter, immobilization of dissolved oxidizable carbon by soil microbes and release of carbon as carbon dioxide and methane.

$$\begin{aligned} \text{DOC} &= \text{CARDEC} + \text{CELDEC} + \text{LIGDEC} + \text{SOCDC1} + \text{SOCDC2} + \\ &\text{SOCDC3} - \text{CIMMO1} - \text{CIMMO2} - \text{CIMMO3} - \text{CO2EMS} - \text{CHEMIT} \\ \text{CDOC} &= \text{INTGRL}(\text{ZERO}, \text{DOC}) \end{aligned}$$

Net organic matter balance (SOCTOT, %) is calculated as

$$\begin{aligned} \text{SOCTOT} &= (\text{SOCLAB} + \text{SOCNT1}) / (\text{TKL1} / 150. * 22000. * \\ &\text{BD1} / 1.56) \\ \text{SOCLAB} &= \text{OM1CAS} + \text{OM2CAS} + \text{OM3CAS} + \text{OM1CLS} + \text{OM2CLS} \\ &+ \text{OM3CLS} + \text{OM1LIS} + \text{OM2LIS} + \text{OM3LIS} \end{aligned}$$

Methane production was considered dependant on different pools of soil carbon and redox potential as described below (Huang et al., 1998):

$$\begin{aligned} \text{CH4PR1} &= 0.27 * (\text{CARDEC} + \text{CELDEC} + \text{LIGDEC} + \text{SOCDC1}) * \\ \text{EHCF} \\ \text{CH4PR2} &= 0.27 * \text{SOCDC2} * \text{EHCF} \\ \text{CH4PR3} &= 0.27 * \text{SOCDC3} * \text{EHCF} \end{aligned}$$

where CHPR 1 to 3 are the methane production ($\text{kg ha}^{-1} \text{ day}^{-1}$) in soil layers 1 to 3; CARDEC, CELDEC and LIGDEC are the amounts (kg ha^{-1}) of dissolved oxidizable carbon substrate available through the mineralization of added carbohydrate, cellulose plus hemicellulose and lignin, respectively; SOCDC 1 to 3 are dissolved oxidizable carbon available (kg ha^{-1}) through the degradation of soil organic carbon; 0.27 is the ratio of the molecular weights of methane and carbohydrate assuming that three moles of methane (CH_4) is derived from one

carbohydrate unit ($0.27 = 3 \text{ CH}_4/\text{C}_6\text{H}_{12}\text{O}_6$) (Huang et al., 1998a); and EHCF is the factor for redox potential in soil which is a function of days after flooding/ponding the soil (Mitra et al., 2002a, 2002b).

$$\text{EHCF} = \text{AFGEN} (\text{EHFAC}, \text{EH})$$

$$\text{EH} = \text{AFGEN} (\text{MTABEH}, \text{DAPOND})$$

Total production of methane (CH_4TOT , $\text{kg ha}^{-1} \text{ day}^{-1}$) is the sum of methane produced in different layers 1 to 3 of the soil profile ($\text{CH}_4\text{PR1} + \text{CH}_4\text{PR2} + \text{CH}_4\text{PR3}$).

$$\text{CH}_4\text{TOT} = (\text{CH}_4\text{PR1} + \text{CH}_4\text{PR2} + \text{CH}_4\text{PR3}) * 0.55$$

The constant 0.55 represents the initial fraction of methane produced which is emitted, because considerable amount of methane produced in soil gets oxidized while emitting to the atmosphere (Huang et al., 1998a).

Once methane has been produced in soil it escapes to the atmosphere mainly by three mechanisms: vascular transport, ebullition and diffusion. In the vascular transport methane is emitted from paddy fields mostly by transport through plants like rice, if present. Rice plants act as bundles of chimneys to transport CH_4 from the rhizosphere to the atmosphere. Aerenchyma helps in transport of O_2 and some other gases in a number of aquatic plants as well as in rice. The contribution of ebullition to total CH_4 emission is not more than 20%. It has been observed that fields without rice plants emit 50% methane of the amount of CH_4 emitted by the fields planted with rice. The actual diffusion of CH_4 from rice fields is a function of CH_4 supply

and, CH₄ concentration in the floodwater. Diffusion through the floodwater is usually less than 1% of the total flux. Therefore, in the InfoCrop methane emission through ebullition and diffusion processes has been calculated as a single process. Thus methane emission (CHEMIT) = CHVASC + CHEBUL, Where CHVASC and CHEBUL are methane emissions through vascular transport and ebullition plus diffusion, respectively. Methane emission (kg ha⁻¹ day⁻¹) through vascular transport is calculated using empirical relationship between total methane production in soil (CHSOIL) and total above ground biomass of the crop (TDM) as given below.

$$\text{CHVASC} = \text{AMAX1}(0., \text{CHSOIL} * \text{LIMIT}(0, 1., (\text{TDM}/15000.) + .2))$$

The remaining methane is escaped to the atmosphere through ebullition plus diffusion, which is also depended upon the depth of ponded water (POND).

$$\text{CHEBUL} = \text{AMAX1}(0., (\text{CHSOIL} - \text{CHVASC}) * \text{AFGEN}(\text{EBULTN}, \text{POND}))$$

The amount of dissolved oxidizable carbon (CDOC) left after emission of methane (CH₄SUM) is emitted as CO₂ (CO₂EMS, kg ha⁻¹ day⁻¹), with a time coefficient (TCOEFF) of 10.

$$\text{CO}_2\text{EMS} = \text{AMAX1}(0., \text{CDOC} - \text{CH}_4\text{SUM}) / \text{TCOEFF}$$

$$\text{CO}_2\text{SUM} = \text{INTGRL}(\text{ZERO}, \text{CO}_2\text{EMS})$$

Calibration and Validation of the model

Two independent field experiments- one short term and another long term- were used for calibrating the carbon dynamics of the InfoCrop model. The experimental results reported earlier were not used for validation, because the relationship between MBC and SOC used in the model was based on this experiment.

Short-term changes in carbon

A comparison of measured and simulated values of biomass, grain yield, CH₄ emission and CO₂ emission for control, 100% NPK and Urea + FYM treatments are shown. The model simulated reasonably well the total biomass and grain yield in rice grown in 1999 with saturation moisture regime (Fig. 12 and 13). In the same year, in case of intermittent wetting and drying moisture regime the grain and biomass yields were well simulated by the model for control as well as NPK+FYM treatment. However, the model overestimated both biomass and grain yield when NPK alone was applied (Fig. 12 and 13). The CH₄ emission from rice field was also simulated for both water management regimes. In saturated moisture regime the simulated values of CH₄ emission were slightly less than the measured one in control and 100% NPK treatment (14a). The model simulated comparable values of CH₄ emissions in intermittent irrigation regime for control as well as urea alone treatment (Fig. 14b). However, in both water regimes, model overestimated CH₄ emission for FYM alone and in urea + FYM treatment.

Similarly in intermittent wetting and drying moisture regime the model predicted very high value (47 kg ha^{-1}) of CH_4 emission in urea + FYM treated plot as compared to the observed one (27.7 kg ha^{-1}) (Fig. 14).

In the rice experiment of 2000, model simulated above ground carbon dynamics in terms of total biomass and grain yield very well, the difference between measured and simulated values being very small (Fig. 18). This was true for all treatments of water and nutrient management. CO_2 emissions were measured for different treatments in this crop season. The model again showed very accurate results for CO_2 emissions for all treatments (Fig. 19).

In case of wheat, measured data of 1999 experiment alone was available. The treatments varied in irrigation management as well as application of inorganic and organic fertilizer. The InfoCrop model was able to reasonably simulate the grain as well as biomass yield in all treatments (Fig. 15 and 16). CO_2 emission from the crop were also measured in this crop seasons in all treatments. The simulated CO_2 emission were 10-20% less than the measured values in different treatments (Fig. 17).

Long-term changes in carbon

A long-term experiment was conducted in Ludhiana in rice-wheat cropping system for 14 years (1985-1997). Measurements of yield of both rice and wheat crops in different treatments of NPK management were available. Occasionally soil

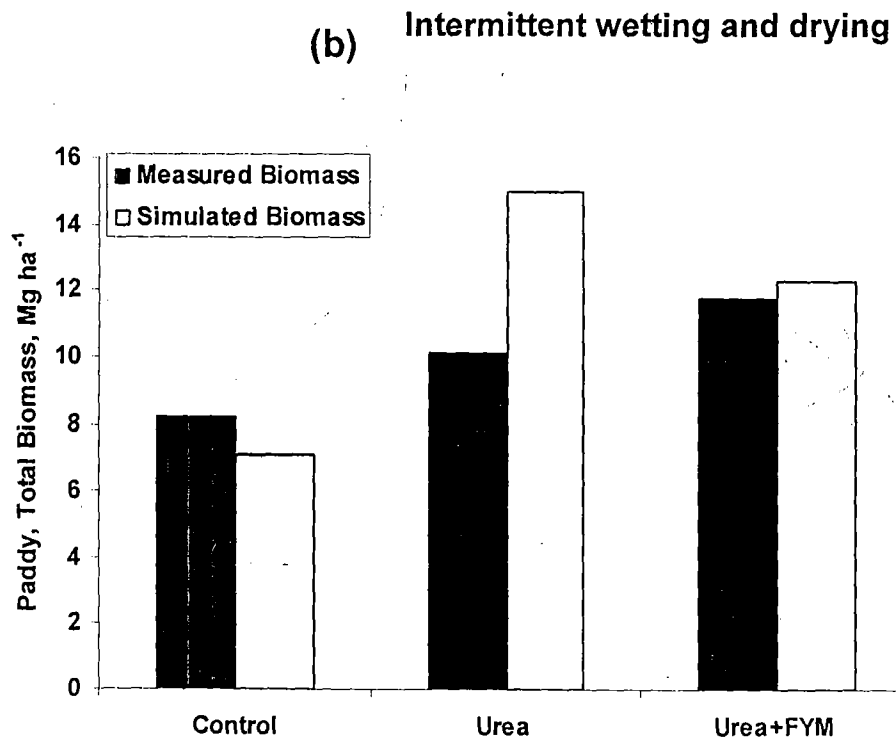
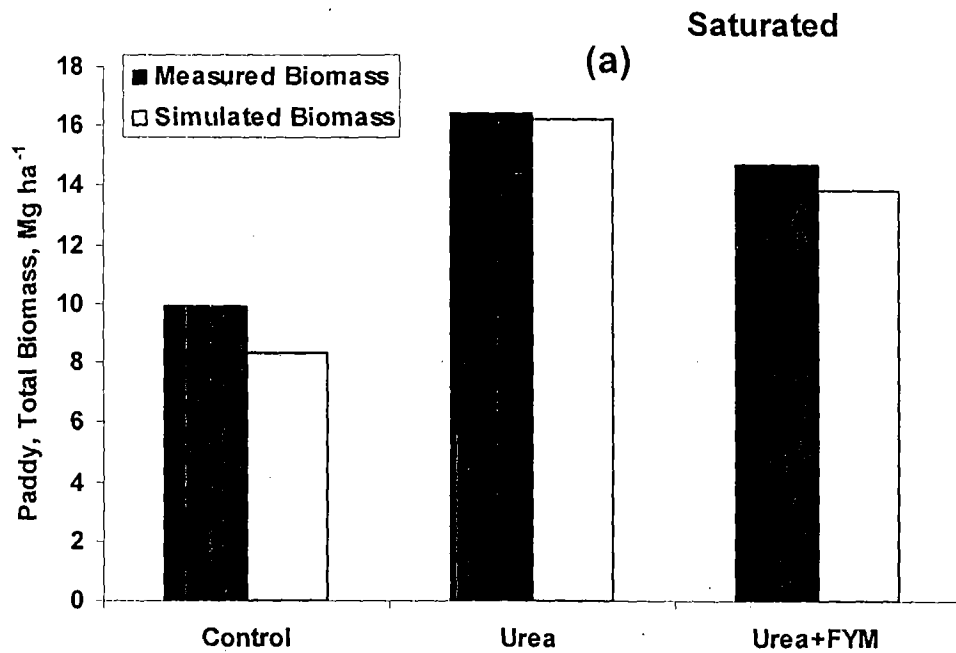


Fig. 12 Simulated and observed biomass yield of rice in 1999

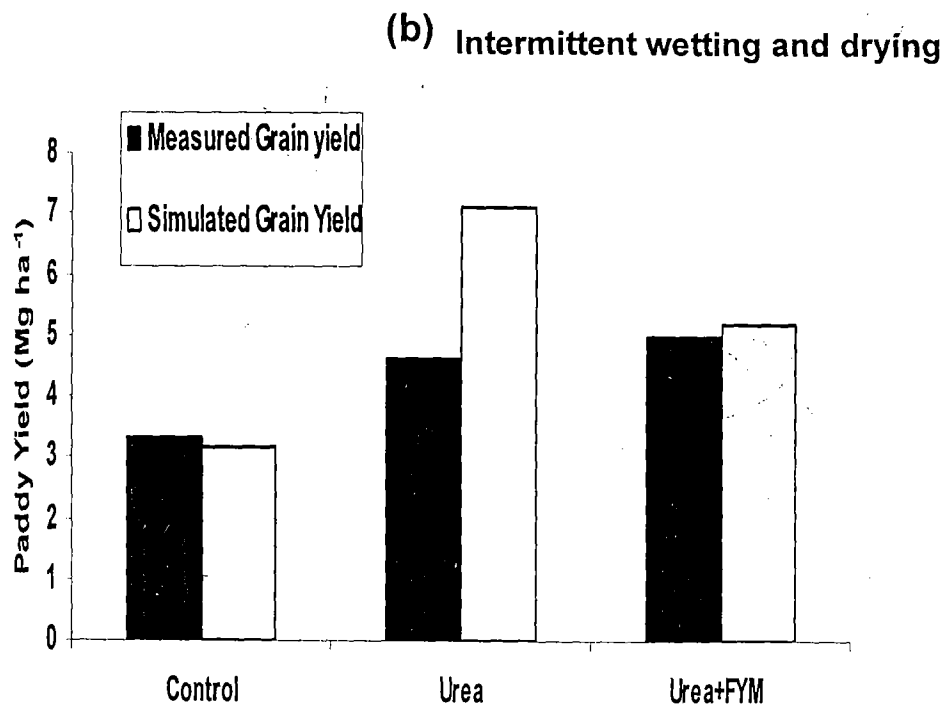
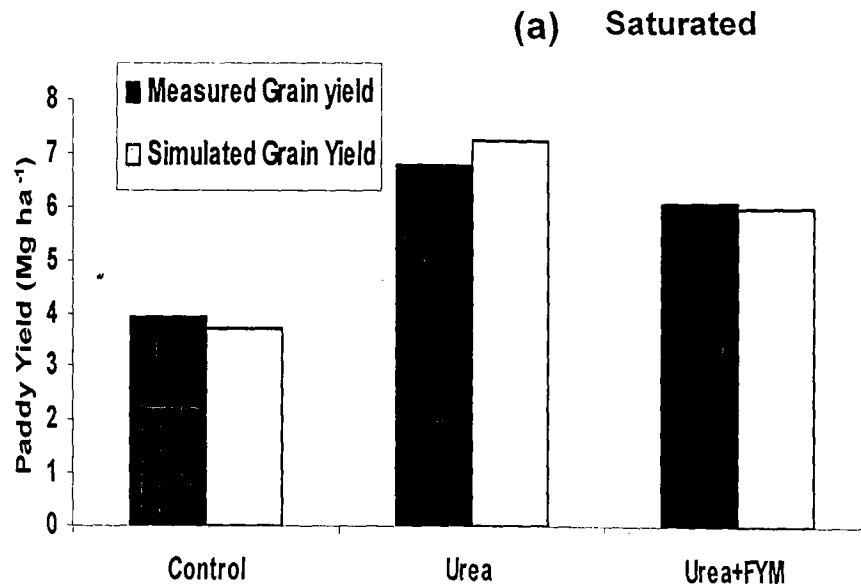


Fig. 13 Simulated and observed grain yield of rice in 1999

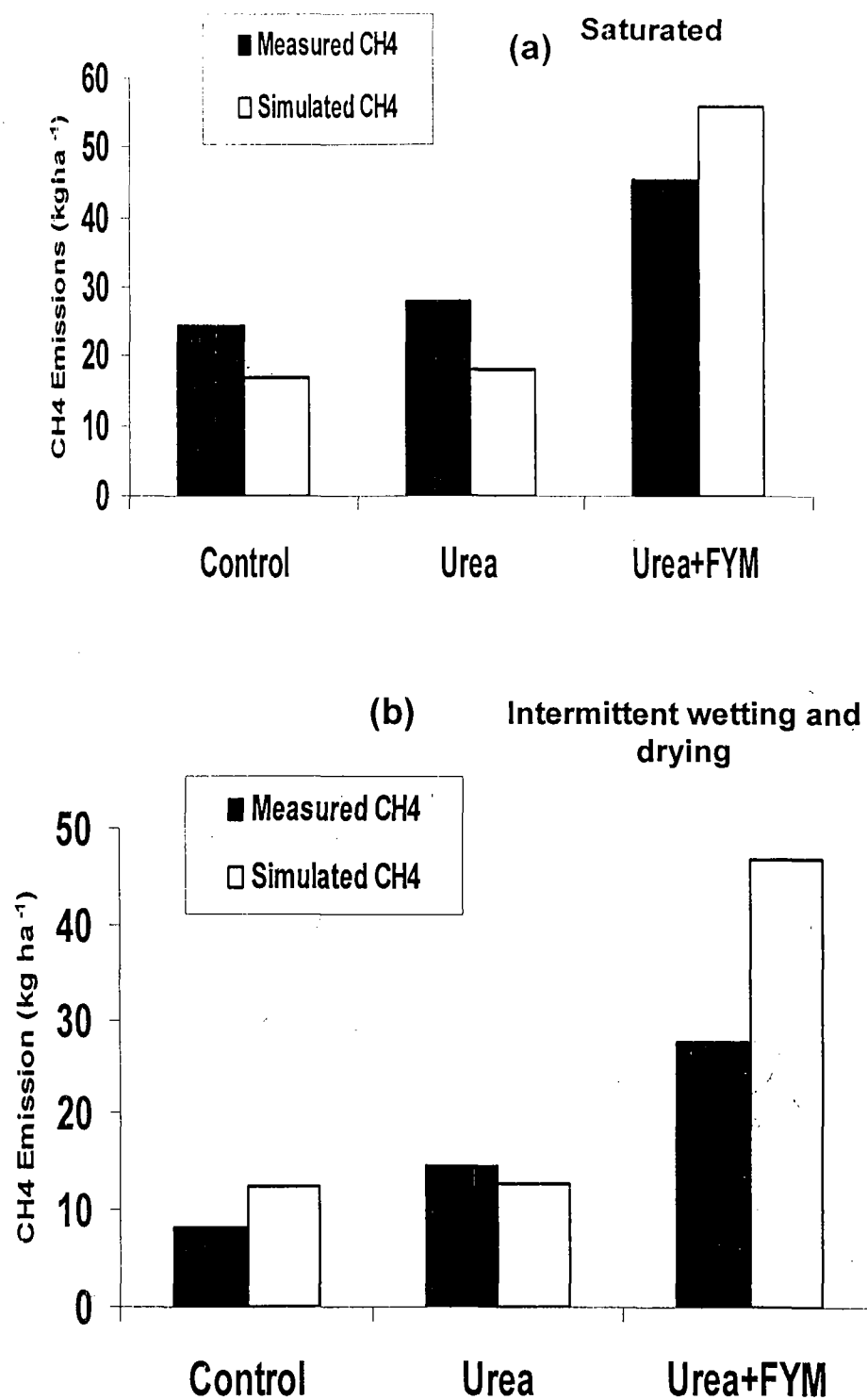


Fig. 14 Simulated and observed CH₄ emission from rice field in 1999

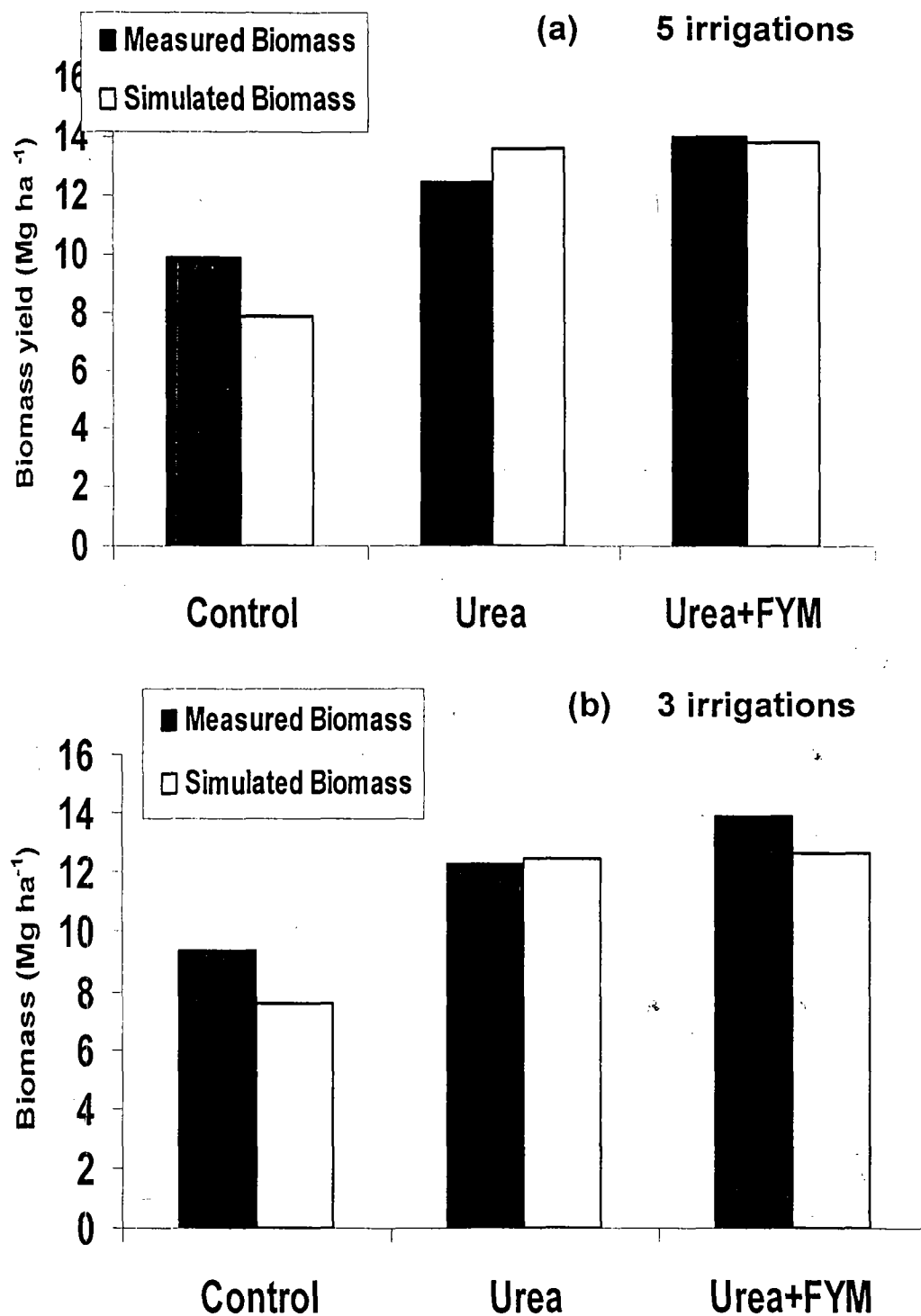


Fig. 15 Simulated and observed biomass yield of wheat in 1999

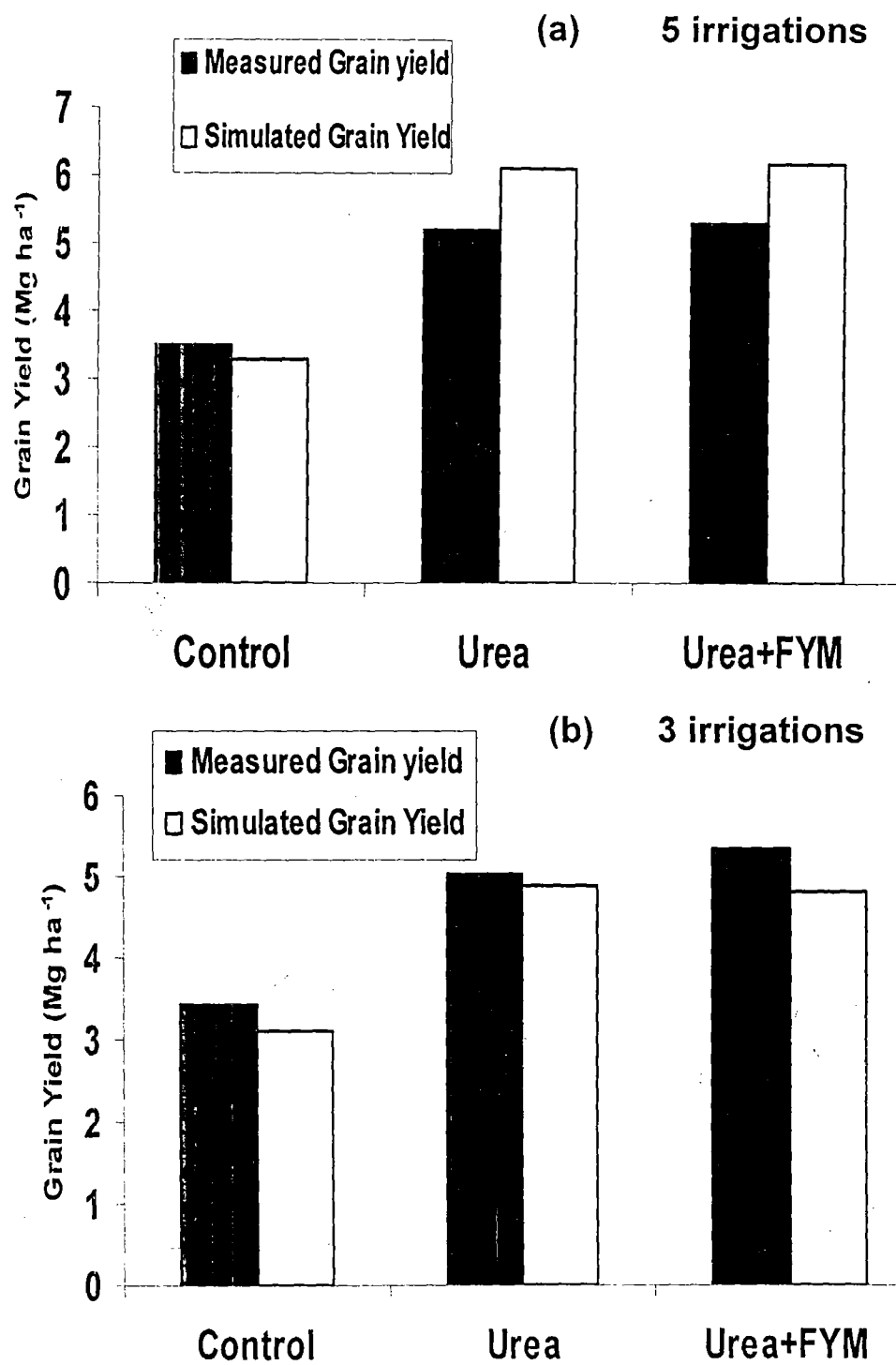


Fig. 16 Simulated and observed grain yield of wheat in 1999

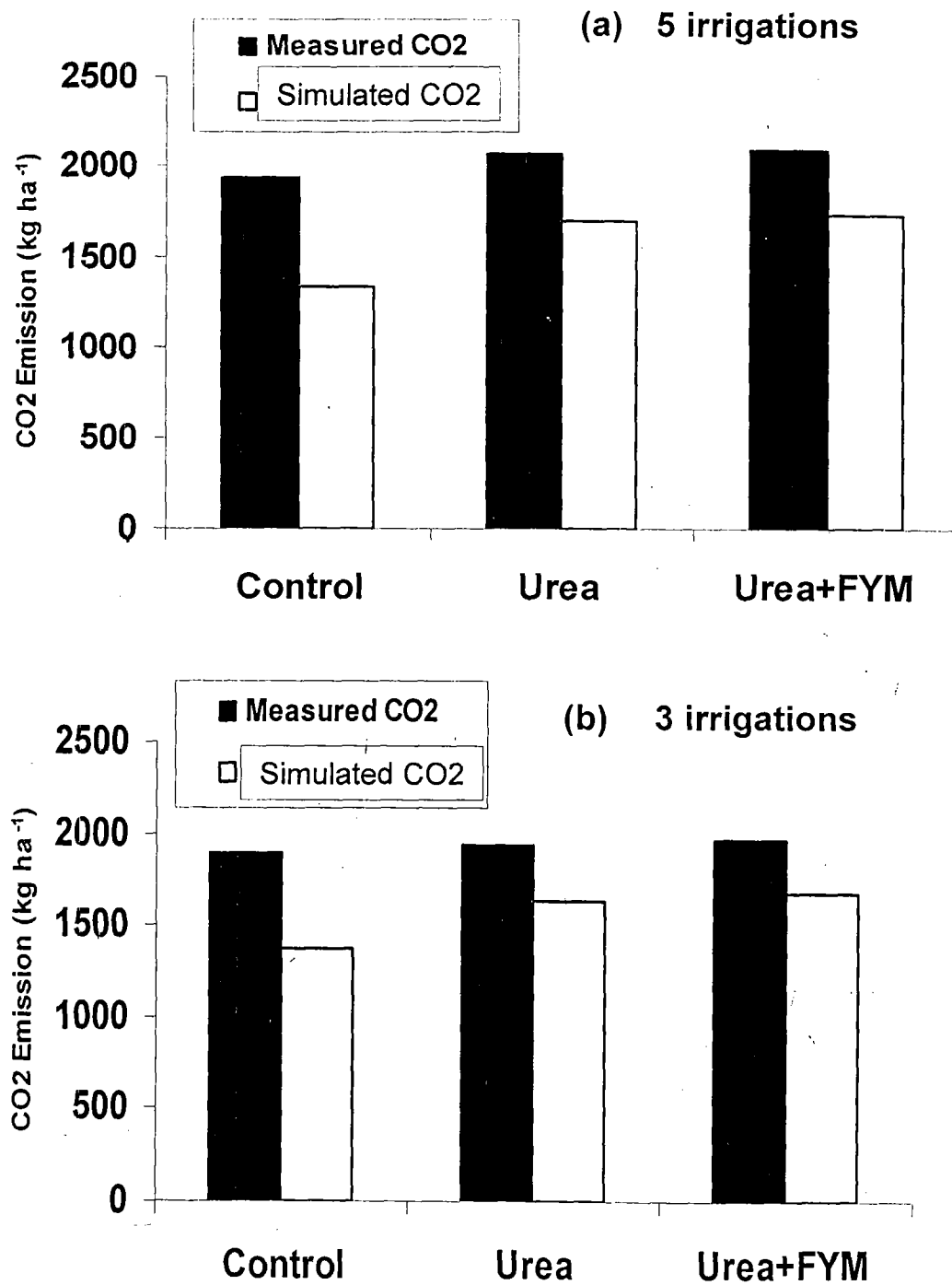


Fig. 17 Simulated and observed CO₂ emission from wheat field in 1999

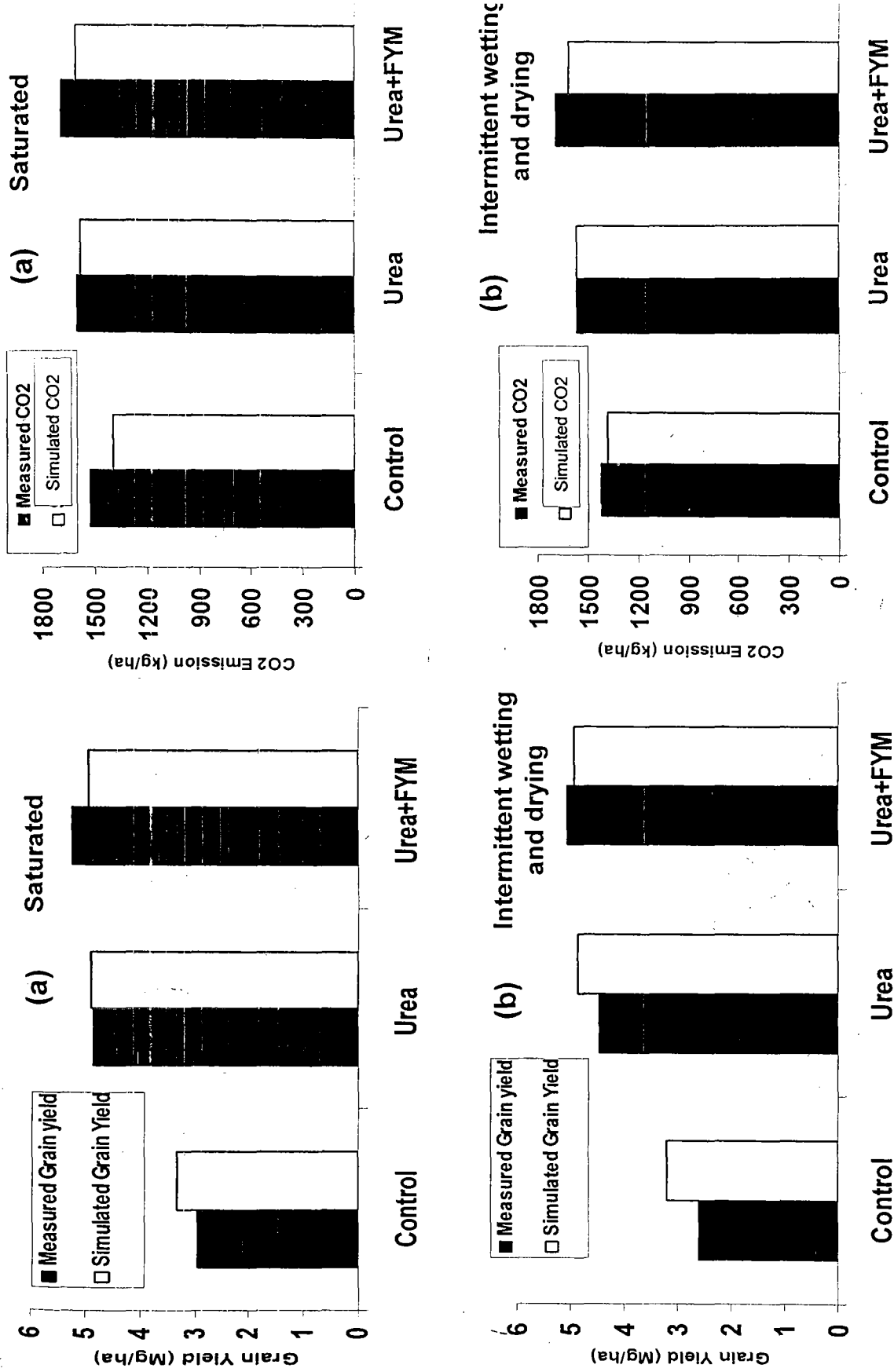


Fig. 18 Simulated and observed grain yield of rice in 2000

Fig. 19 Simulated and observed CO₂ emission from rice field in 2000

organic carbon was also measured for the surface soil layer. Complete details needed for a proper calibration and validation of the model were not available from the experiment. Therefore, this experiment was used to validate only the relative trends of change in grain yield as well as SOC.

Simulated grain yields of paddy were not necessarily similar to measured yields in different years. This could be partly due to inadequate calibration of the model due to limited measured data. Measured rice yields indicated a slight declining trend in yield in all treatments irrespective of the nutrient management (Fig. 20 and 21).

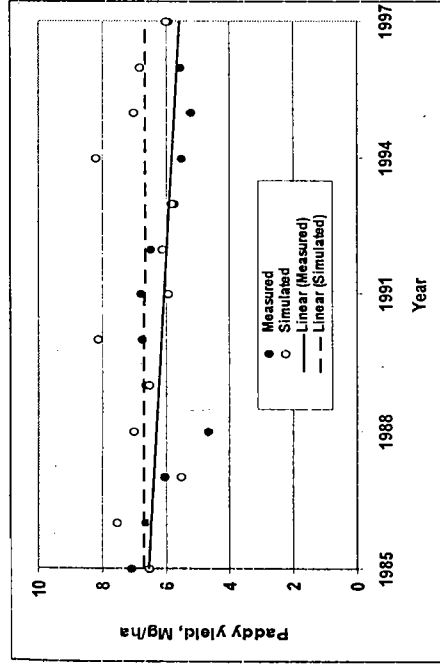
Simulated paddy yields, however, showed no significant trend in all treatments.

In case of wheat, the absolute values of simulated yields were generally higher than the measured values in all treatments. This difference sometimes was almost 1.0 t/ha. The data indicated that simulated yields of wheat showed a decreasing trend in all treatments, except in control where there was no decrease (Fig. 24).

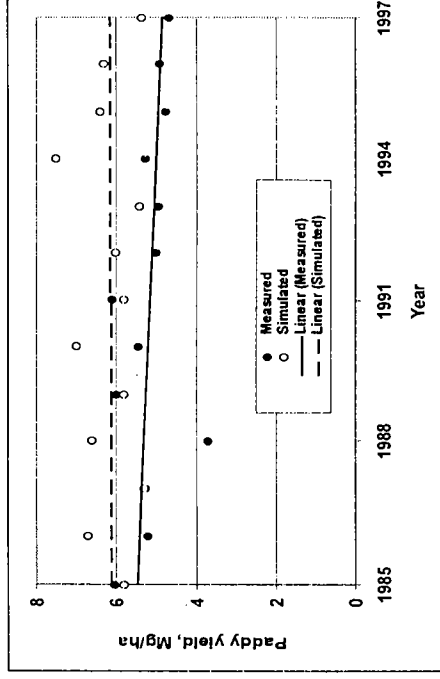
The trends in simulated wheat yields were more or less similar to the measured trends in all treatments, indicating models relative capability to simulate long-term changes once properly calibrated.

The measurements of soil organic carbon were made only in few years in some selected treatments. These are plotted along with the simulated SOC for the selected treatments for rice and wheat in Fig. 22 and 25. In 50% NPK + green manure treatment in rice, simulated values of organic carbon increased from 0.4%

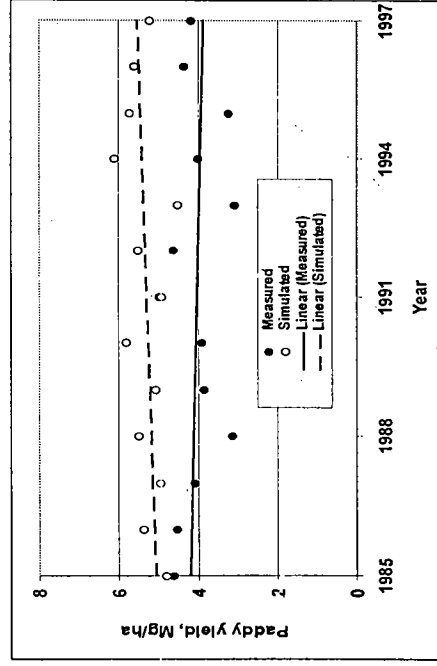
(a) 100% NPK



(c) 75% NPK



(b) 50% NPK



(d) 50% NPK + FYM

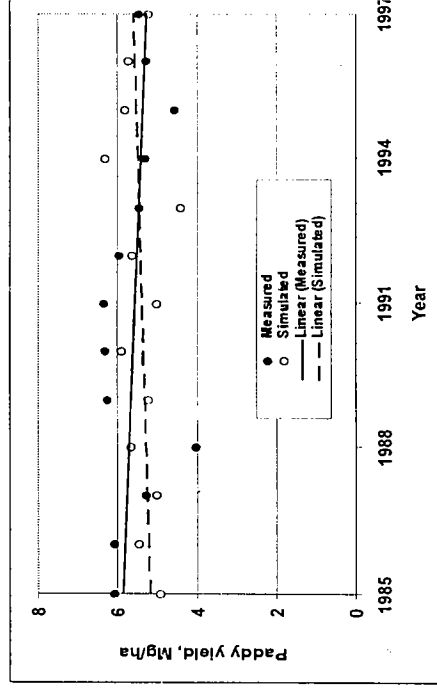
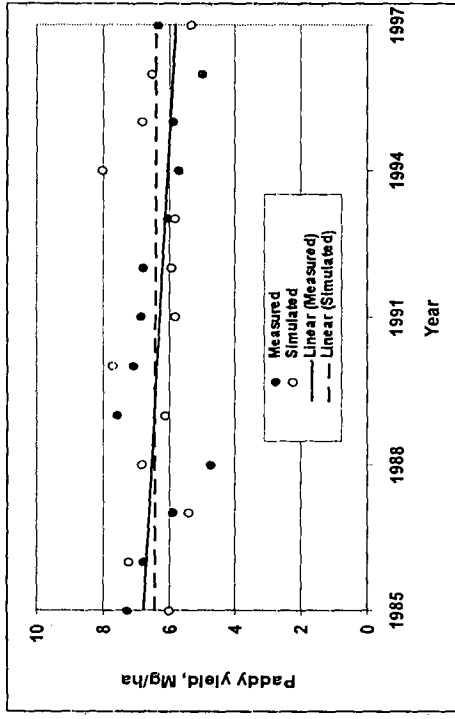
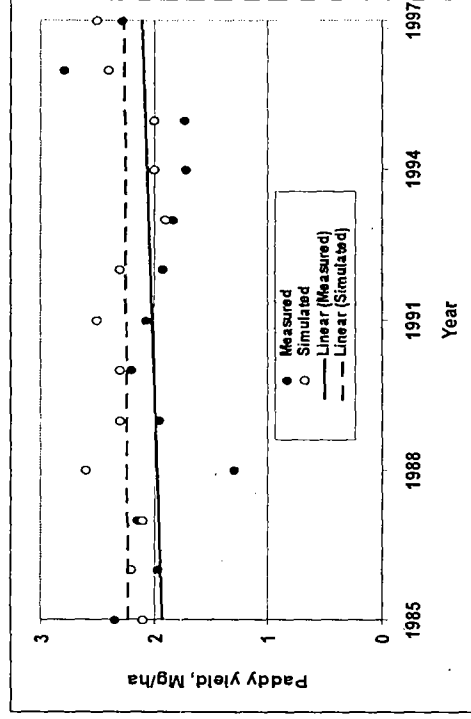


Fig. 20 Simulated and observed yield of rice in long term experiment with different fertilizer treatments

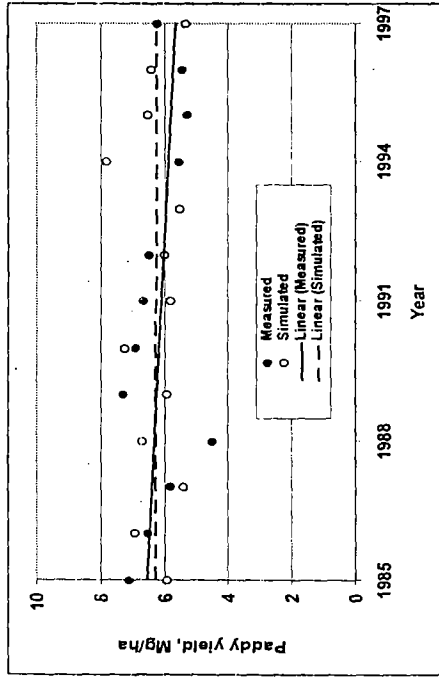
(c) 75% NPK + Green manure



(d) Control



(a) 50% NPK + Green manure



(b) 75% NPK + FYM

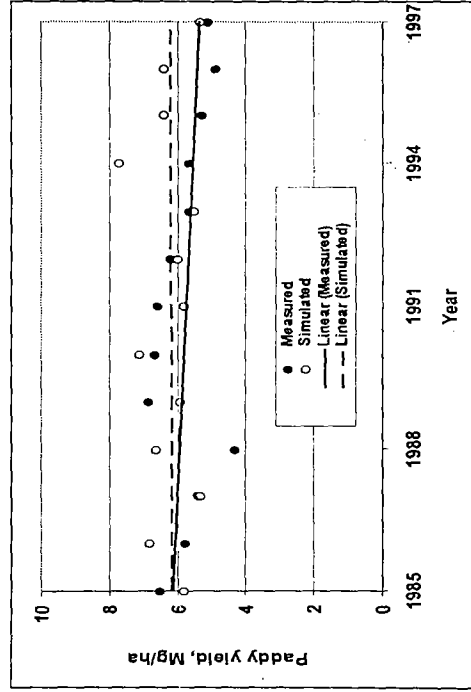
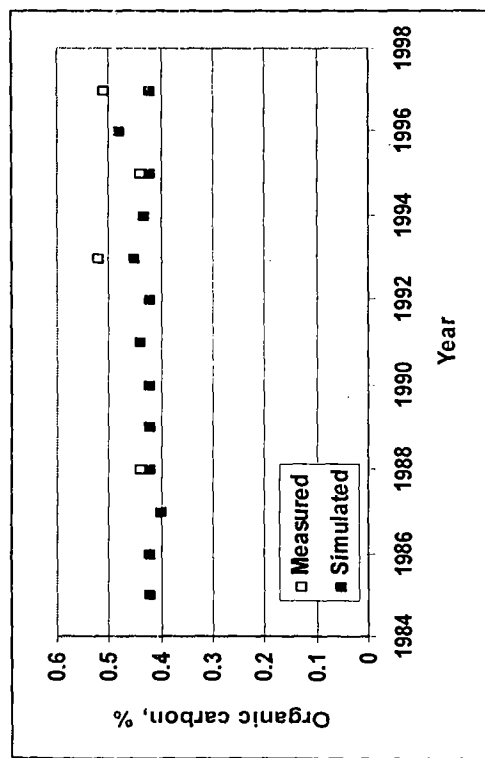
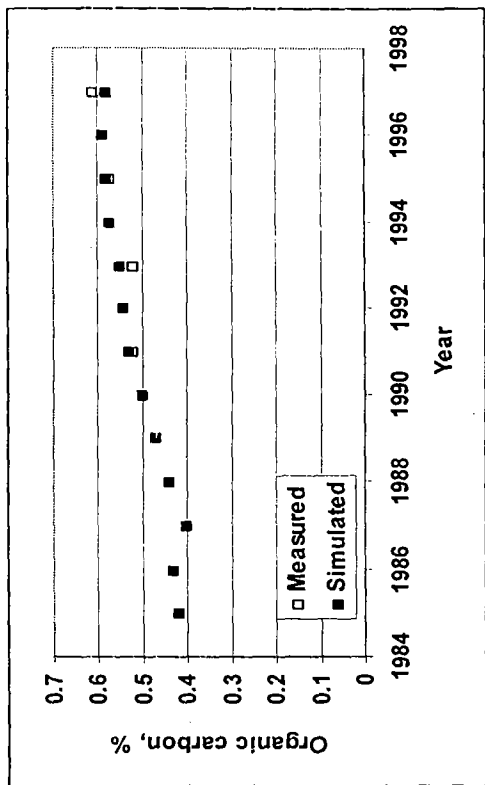


Fig. 21 Simulated and observed yield of rice in long term experiment with different fertilizer treatments

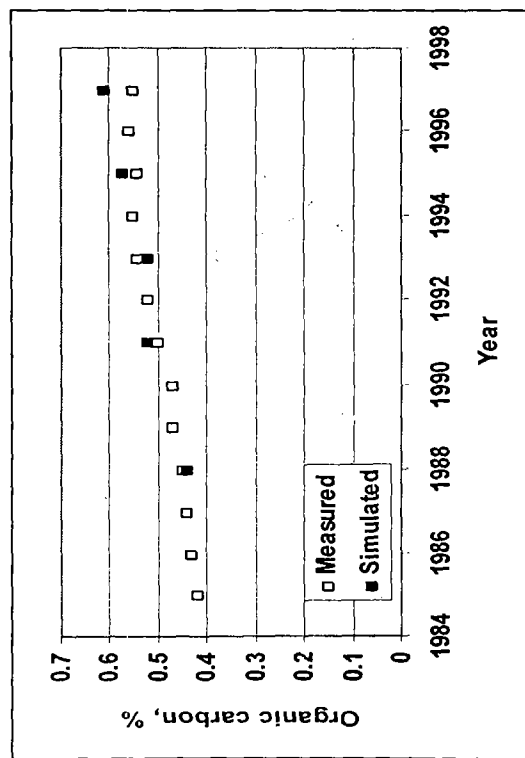
(a) 100% NPK



(c) 50% NPK + FYM



(b) 50% NPK + Green manure



(d) Control

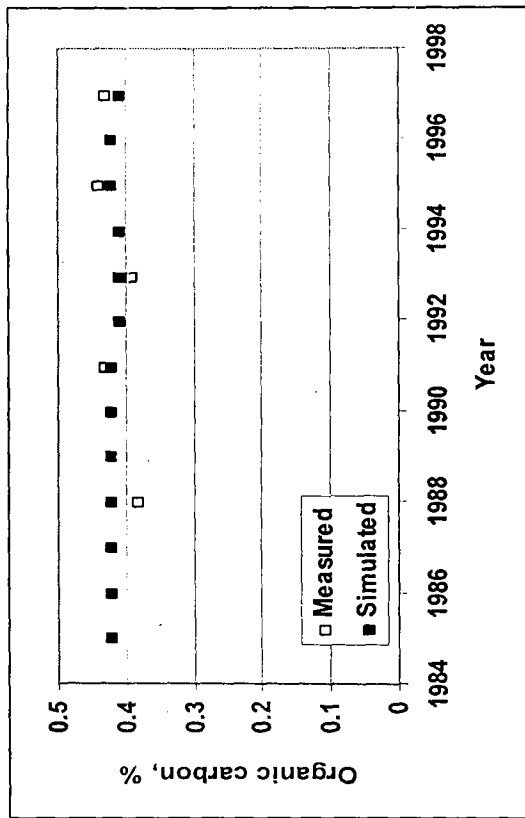
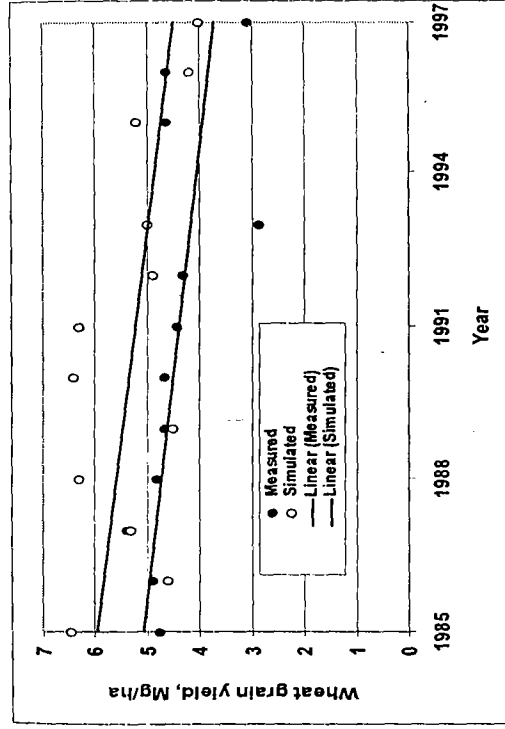
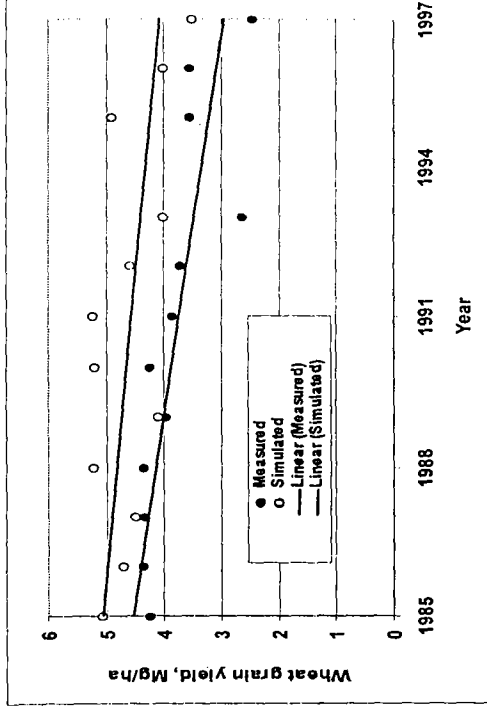


Fig. 22 Simulated and observed organic carbon of rice soil in long term experiment with different fertilizer treatments

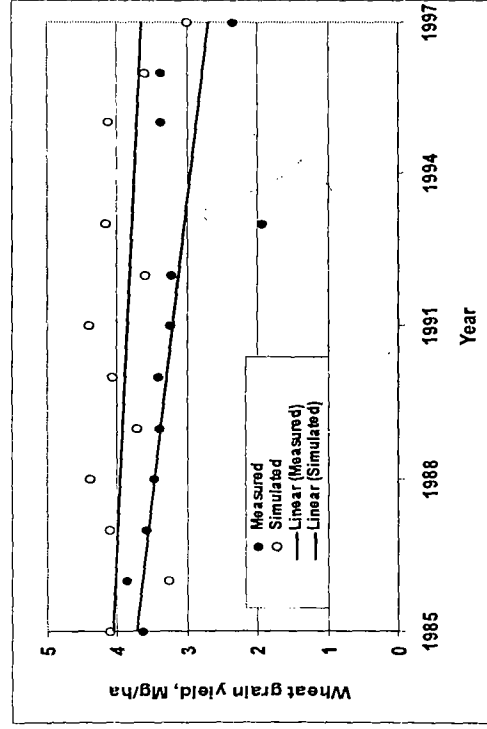
(a) 100% NPK



(c) 75% NPK



(b) 50% NPK



(d) 50% NPK + FYM in rice
& 100% NPK in wheat

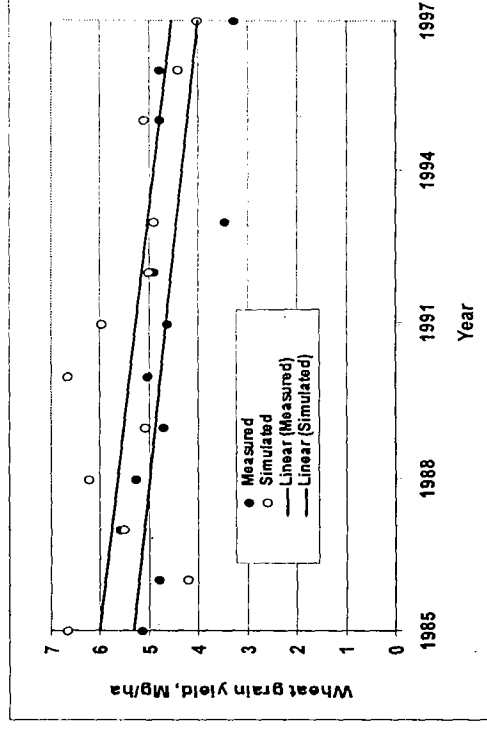
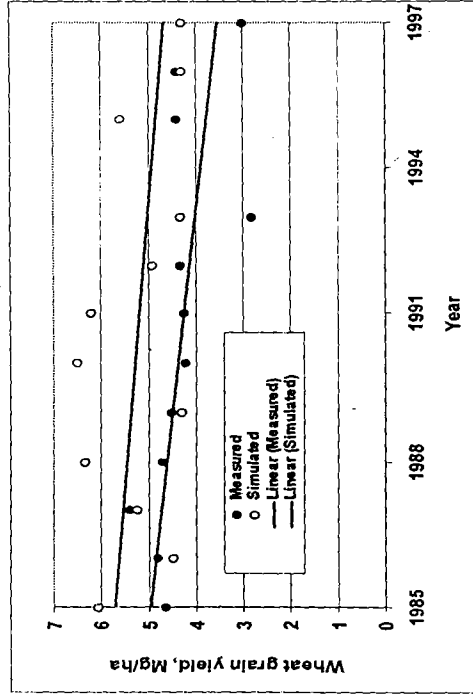
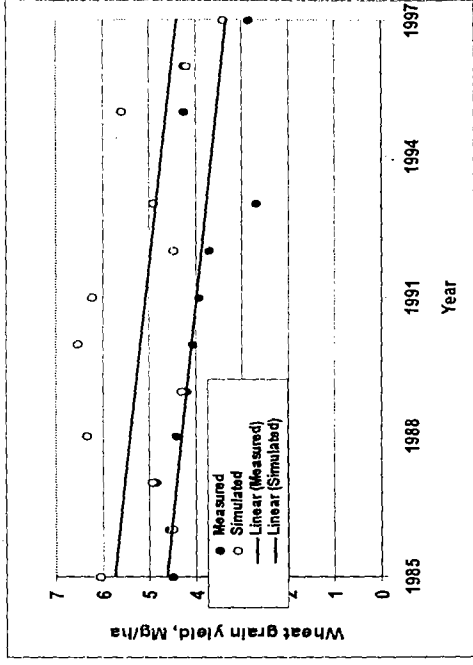


Fig. 23 Simulated and observed yield of wheat in long term experiment with different fertilizer treatments

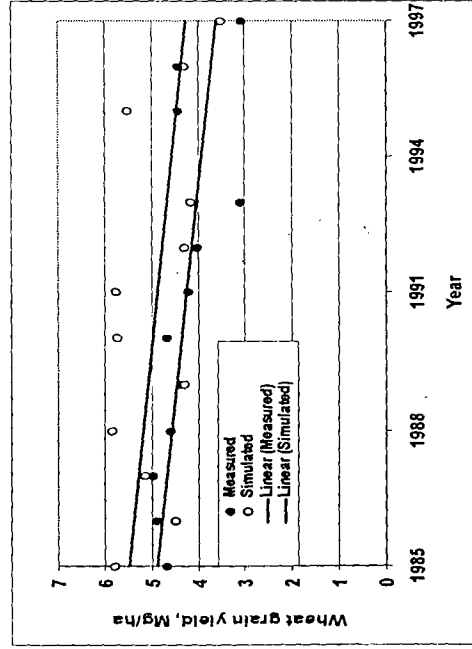
(a) 50% NPK + Green manure in rice & 100% NPK in wheat



(c) 75% NPK + Green manure in rice & 75% NPK in wheat



(b) 75% NPK + FYM in rice & 75% NPK in wheat



(d) Control

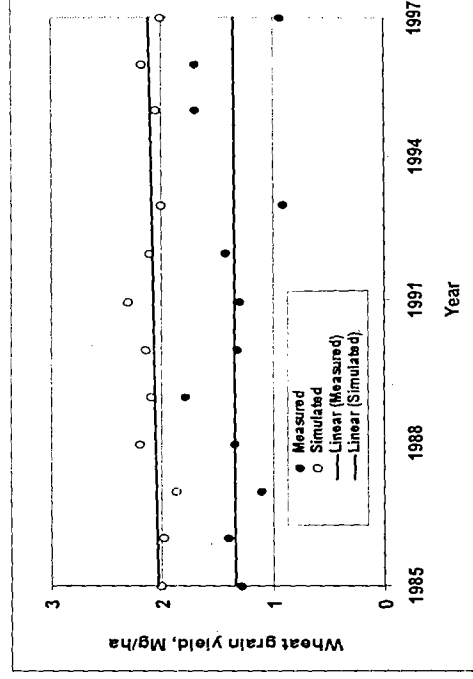
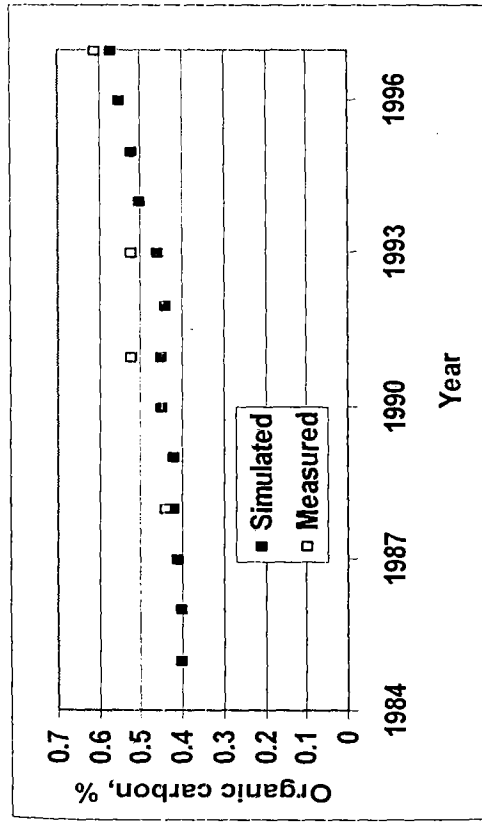
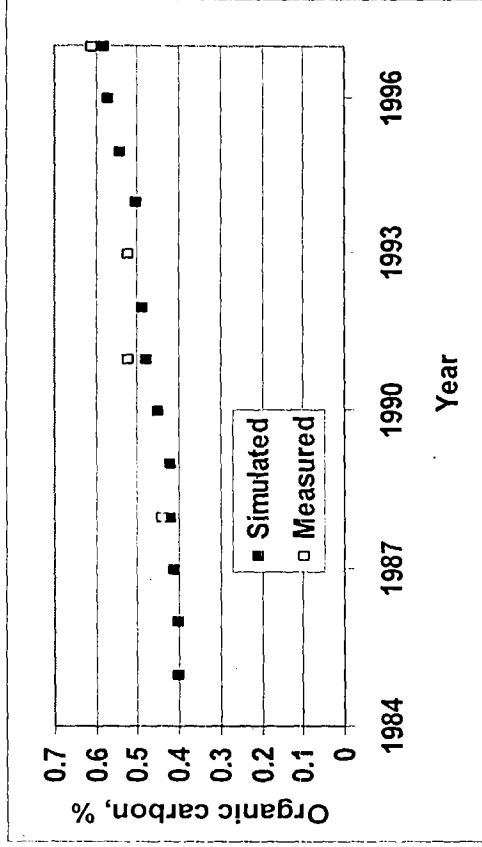


Fig. 24 Simulated and observed yield of wheat in long term experiment with different fertilizer treatments

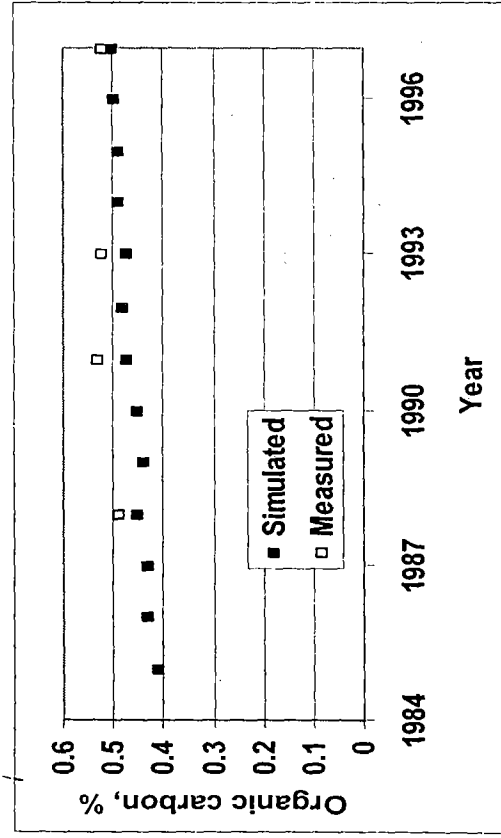
(a) 100% NPK



(c) 50% NPK + Green manure



(b) 50% NPK + FYM



(d) Control

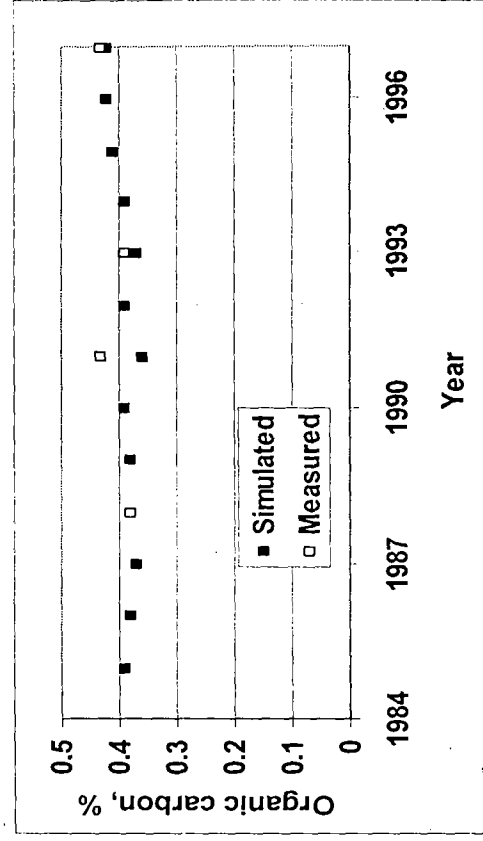


Fig. 25 Simulated and observed organic carbon of wheat soil in long term experiment with different fertilizer treatments

to 0.55% over the years (Fig. 22) while in 50% NPK + FYM treatment it increased from 0.4% to 0.59% (Fig. 22c). Application of organic carbon in the form of green manure and FYM resulted in increasing simulated SOC and it matched with the recorded values, which also showed an increasing trend. In control and 100% NPK treatments both observed and simulated values of SOC were almost same (Fig. 22a and 22d).

In wheat crop also model nicely simulated soil organic carbon and the observed and simulated values are very much similar. Simulated soil organic carbon increased from 0.4% to 0.48% in 100% NPK treatment while observed value was 0.5% at the end (Fig. 25a). In 50% NPK + FYM and 50% NPK + green manure treatment both observed and simulated values of SOC are same and in 1996 it was 0.4% (Fig. 24b and 25c). In control treatment there was no marked change in soil organic carbon (Fig. 25d). Since no fertilizer or organic manure was applied in control plot, there was no much change in soil organic carbon. In 100% NPK treatment application of fertilizer resulted in better crop growth, which led to more amount of root residues in soil and enhanced SOC. These results indicate a very satisfactory simulation of SOC by the InfoCrop in all treatments.

Several long-term trials have been conducted in India and elsewhere where yield trends in intensive rice based cropping systems have been monitored for several years. Dawe et. al. (1999) recently compiled information from 27 long-term rice-

based intensive cropping experiments conducted at 21 sites in tropical and subtropical Asia. These experiments were conducted in a variety of soils and with a range of yield levels and nutrient treatments. This included five long-term fertility experiments on rice-wheat system conducted in India and China. In most cropping systems where rice yields were lower than 6 t ha^{-1} , statistically significant yield declines occurred in only very few experiments. Rice yields declined in one experiment at Pantnagar @ 2.33% per year. This trial was conducted on soil with initially very high organic matter, which declined over time due to non-replacement. Most of the experiments did not show any decline in wheat yields over time. On the contrary, there was a significant although small increase in one trial at Pantnagar, India.

Aggarwal et al. (2000) studied the yield decline in rice-wheat systems for few locations in India. Their results also showed a small but insignificant decline in simulated rice yields at all levels of N management as in our study. Wheat yields declined at potential level but showed no significant trend at other levels. Their results also indicated that the rate of decline in yield could be dependent upon the level of initial yield. Similar yield level dependent trends were observed in the analysis of several long-term fertility experiments recently (Dawe et al., 1999).

Based on above discussion, it can be concluded that the InfoCrop is capable of satisfactorily simulating the carbon dynamics, especially soil organic carbon in

rice-wheat systems. It can also handle the effects of different organic and inorganic nitrogen management strategies as well as the effects of weather and irrigation management. Sometimes, the model did not simulate grain yields correctly. There is a need to examine in more detail the reasons for such discrepancies, which could be related to inadequate model structure, and incomplete parameterisation. Complete validation of the model requires a detailed data set for calibration and initialisation of the model. In most cases, such detailed datasets are usually not available. There is a need to do more rigorous experiments with detailed measurements of soil and plant carbon dynamics.

Simulation of carbon dynamics at different sites in the Indo-Gangetic plains

The validated model was used to simulate the carbon dynamics in rice-wheat system over a period of 10 years at four representative sites of the Indo Gangetic plains namely Delhi, Karnal, Varanasi and Calcutta. Changes in crop yield, soil organic carbon, methane emission and CO₂ emission were recorded at the end of each crop. Results for grain yields are presented as the sum of rice +wheat grain yields.

Delhi

At Delhi control plots (no fertilizer applied) showed stable yield with time although there was a slight negative but non-significant trend (Fig. 26). The mean yields of rice + wheat in this treatment was about 6.5 t/ha. Addition of 100% NPK

(T2) and NPK+FYM (T3) treatment increased yields to 13-15 t/ha but in both cases there was a decreasing trend in yields with time (Fig. 26). The rate of reduction was $0.26 \text{ t ha}^{-1}\text{year}^{-1}$ in T2 as compared to a much slower rate when FYM was applied ($0.12 \text{ t ha}^{-1}\text{year}^{-1}$).

Soil organic carbon decreased in the blank plot (no crop) slightly (Fig. 27). However, in all other cases, there was an increase in SOC with time; the magnitude of increase was largest in NPK+FYM treatment, followed by 100% NPK treatment. This response was similar to the trend in SOC noted in Ludhiana, the data for which was used for calibration. Rekhi et al., (2000) also reported that continuous rice-wheat cultivation in Ludhiana soils with low level of soil organic carbon, resulted in increased SOC with time. On the other hand, Ram (2000) observed that soil organic carbon followed a declining trend in soils with higher organic carbon content (1.48%) in Pantnagar after 8-10 years of cultivation. However, the original status of organic carbon was restored by use of 100% NPK + FYM.

Methane emission from rice fields was simulated for different years and the cumulative values for each year are shown in the figures for different treatments. The emission varied with season and treatment (Fig. 28). The cumulative emissions were $6\text{-}12 \text{ kg C ha}^{-1}$ in control and 100% NPK plots. This was slightly less every year in the blank plot. However, when FYM was added, the emissions increased to

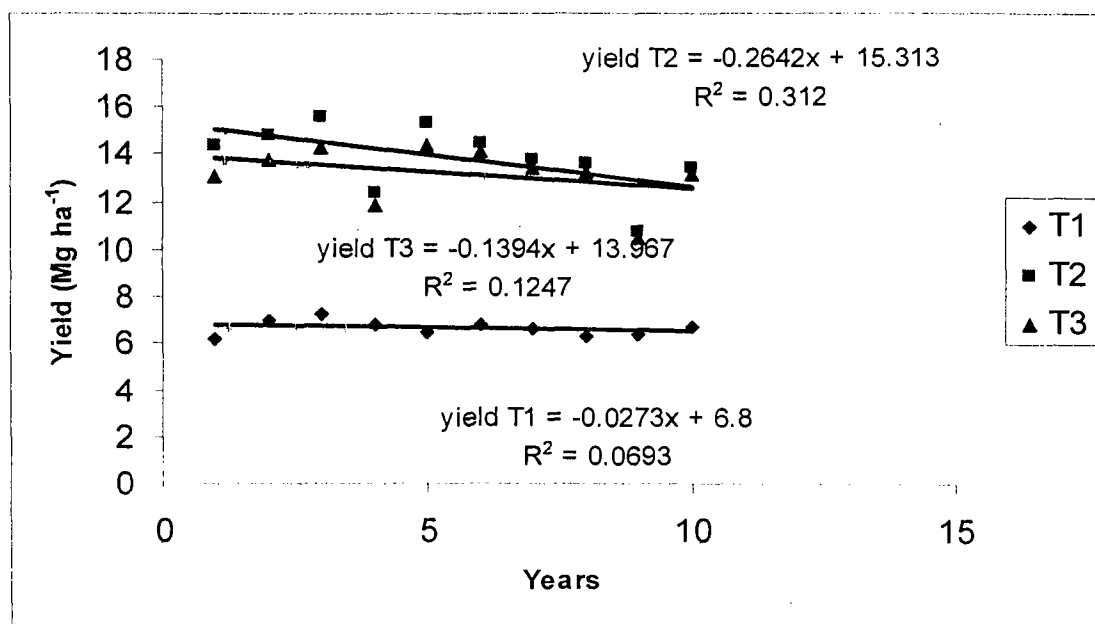


Fig. 26 Rice wheat yield over different years in Delhi

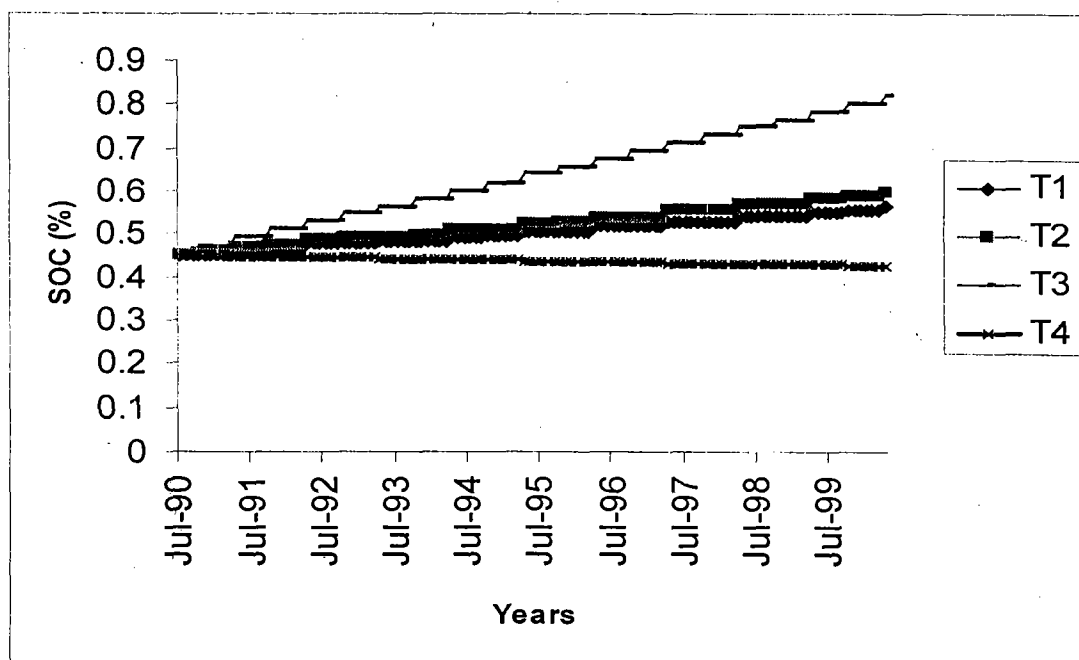


Fig. 27 Changes in soil organic carbon over different years in Delhi

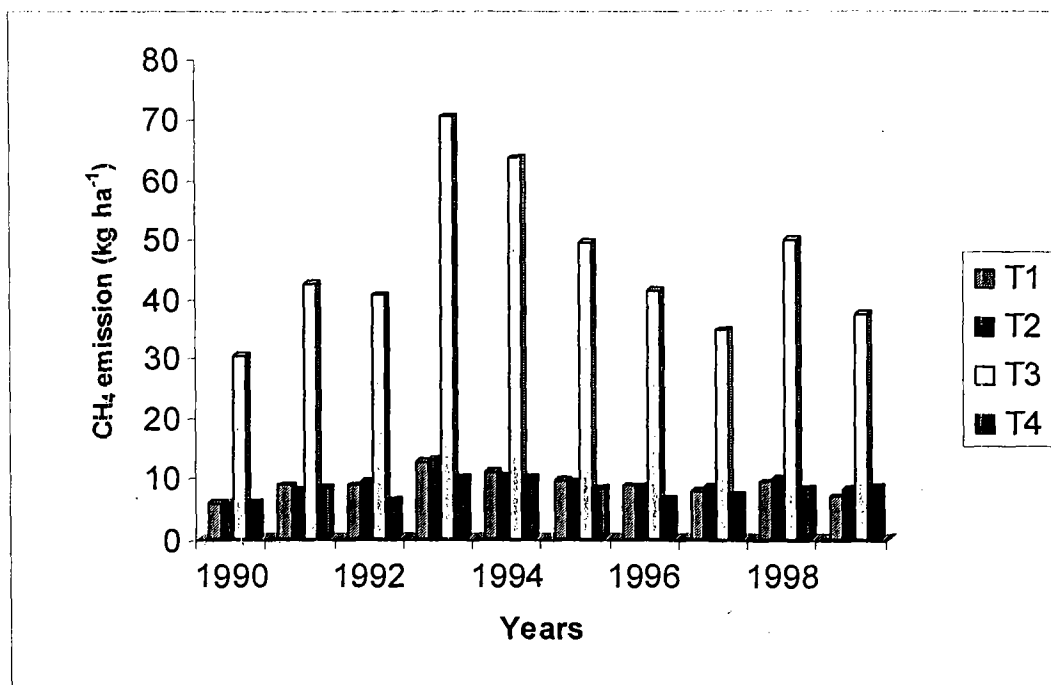


Fig. 28 CH₄ emission from rice field in different years in Delhi

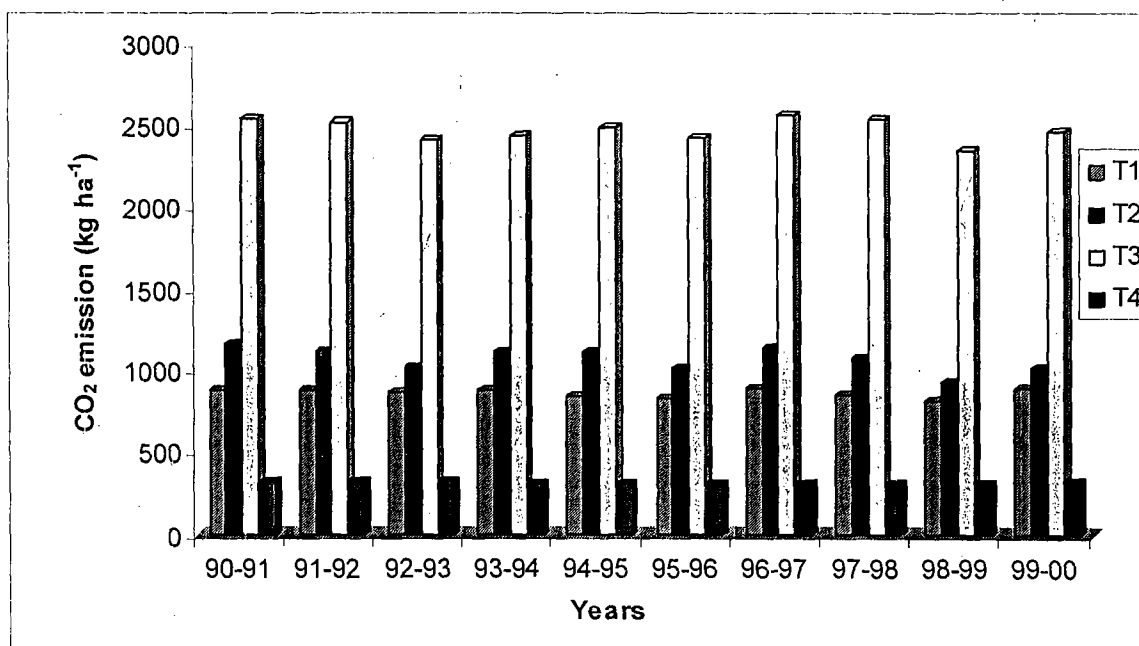


Fig. 29 CO₂ emission from rice wheat field in different years in Delhi

30-70 kg C ha⁻¹year⁻¹. The increased availability of carbon substrate stimulated methanogenesis. Nevertheless, on long-term not all carbon added was lost as there was an evidence of built-up of SOC.

The CO₂ emission also followed a similar trend as that of methane but with varying magnitude. In the blank plots, cumulative emission of CO₂ was 315 kg C ha⁻¹year⁻¹ (Fig. 29). This increased to 850 kg C ha⁻¹year⁻¹ in control plot and to 1037 kg ha⁻¹year⁻¹ in 100% NPK plots. When FYM was applied, the increase was at least double, the mean value reaching 2500 kg C ha⁻¹year⁻¹.

Karnal

Grain yield of rice + wheat in control plots was relatively less than that of Delhi, possibly because of low initial soil organic carbon. When NPK was applied grain yields were similar to Delhi (Fig. 30). However, in comparison to Delhi, all treatments showed a slight positive trend of yield increase over time. In control treatment yield increased to 5.7 tonnes ha⁻¹ from 5.1 tonnes ha⁻¹ (Fig 30). The yield increase in 100% NPK and NPK + FYM treatment was 8.3 and 12.8% respectively. Positive yield trends in rice and wheat could be due to the replacement of cultivars from year to year with better-improved ones. For wheat it is reported that a genetic gain of 1.6% per year has been made in yield since the mid 1960s (Morris *et al.*, 1994; Nagarajan, 1998).

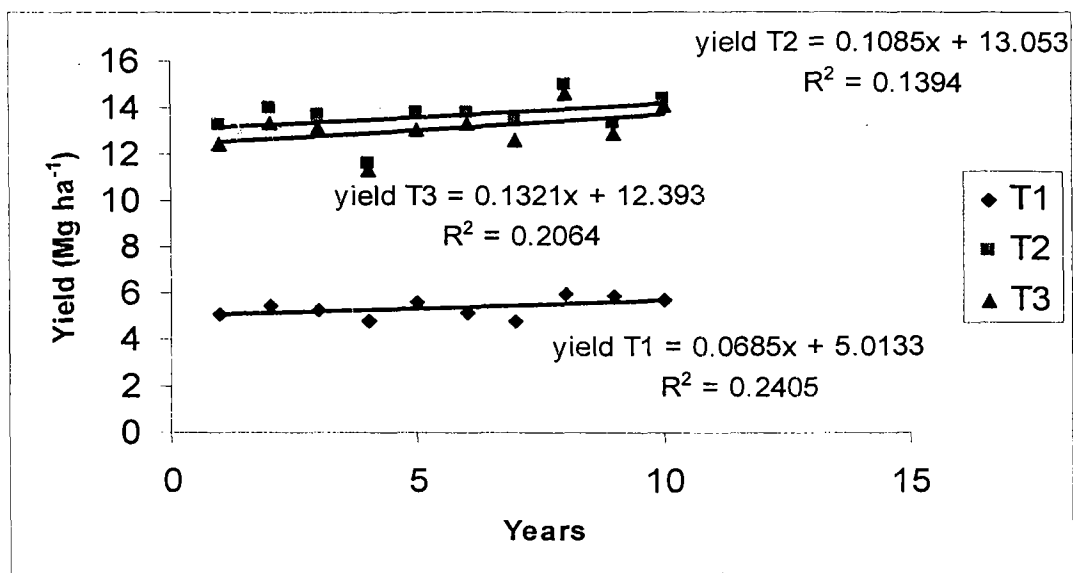


Fig. 30 Rice wheat yield over different years in Karnal

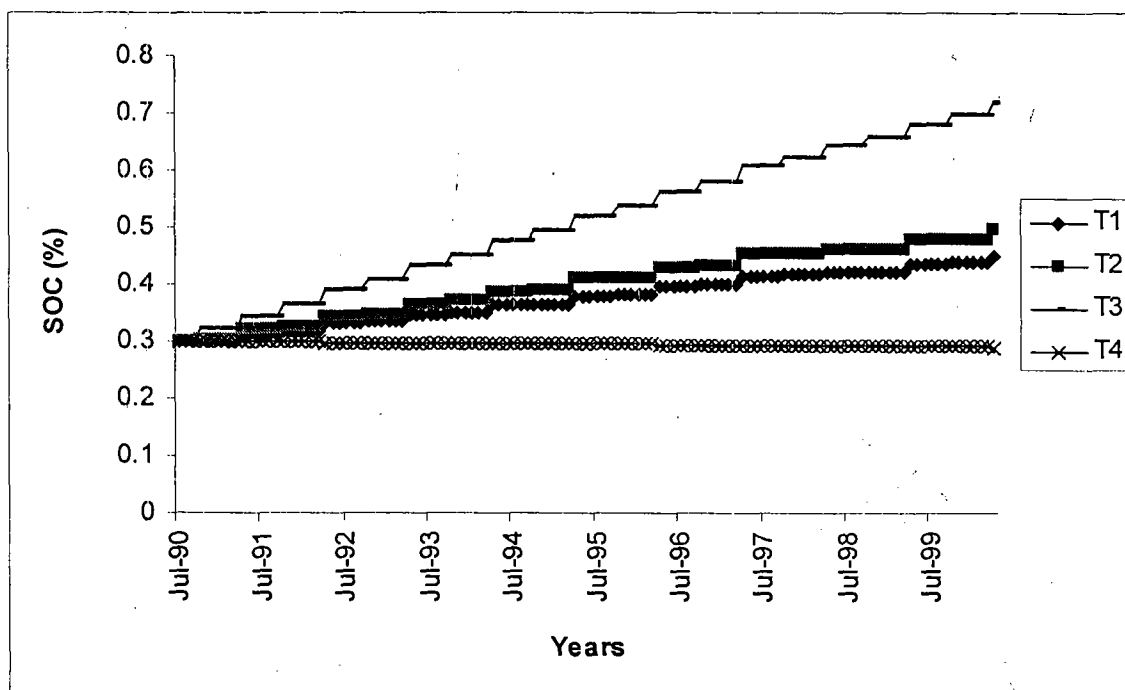


Fig. 31 Changes in soil organic carbon over different years in Karnal

Soil organic carbon level increased from 0.3% to 0.72% in FYM treated plots while in 100% NPK treatment it raised to 0.5% (Fig 31). In blank plot it became 0.29% to 0.3% (Fig 31).

Methane emission was slightly less in Karnal relative to Delhi in all treatments where external organic matter was not applied (Fig. 32). It increased significantly when FYM was added in a pattern similar to that of Delhi. CO₂ emission patterns were also similar to that of Delhi (Fig. 33).

Varanasi

The results of Varanasi in central Indo-Gangetic Plains were very similar to Karnal in north-western part of the Indo-Gangetic plains. Grain yields of rice + wheat increased slightly over the years. 100% NPK treatment recorded almost stable yield but NPK + FYM treatment recorded 3.5 % increase in yield (Fig. 34).

Soil organic carbon showed a 74% increase in FYM treatment. On the other hand there was 6% decline in SOC in blank plot. In 100% NPK treatment (T2) soil organic carbon level increased from 0.5% to 0.63% (Fig 35). The pattern and magnitude of methane and CO₂ emissions were similar to that of Karnal (Fig. 36 and 37).

Calcutta

The grain yields at Calcutta in eastern Indo-Gangetic plains were lower than other parts of the Indo-Gangetic plains due to relatively higher temperatures and lower

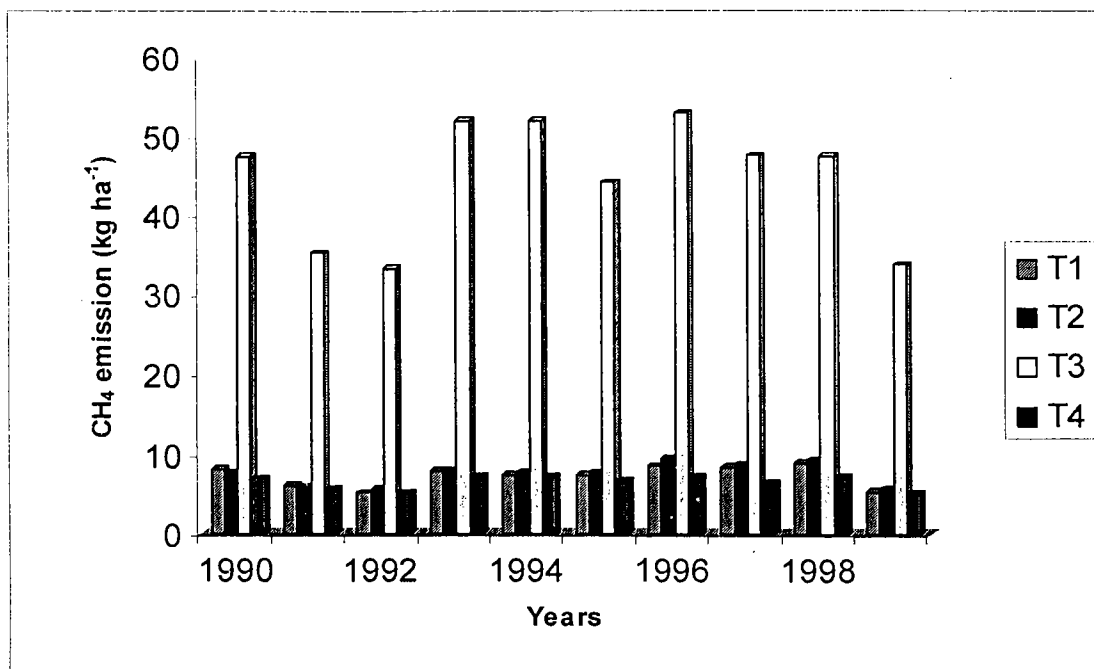


Fig. 32 CH₄ emission from rice field in different years in Karnal

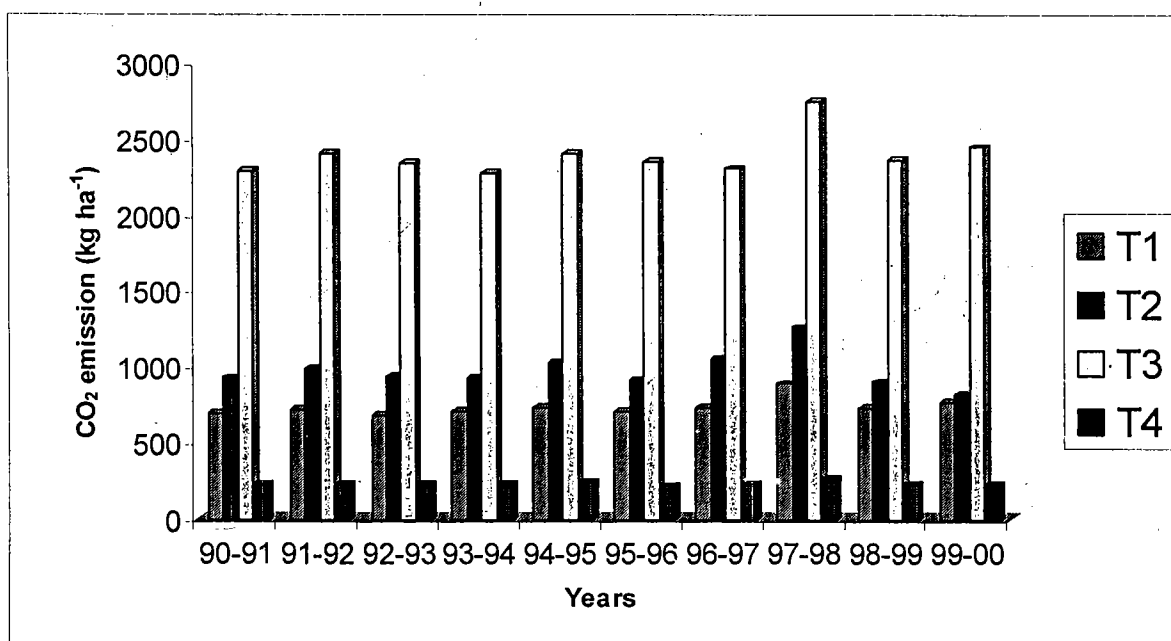


Fig. 33 CO₂ emission from rice wheat field in different years in Karnal

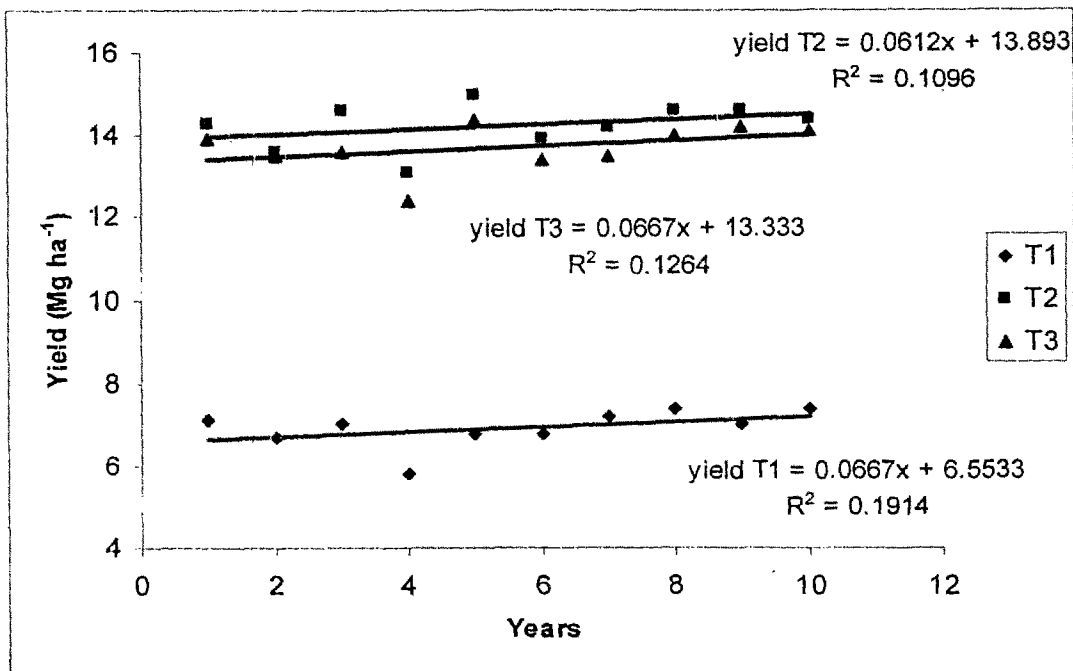


Fig. 34 Rice wheat yield over different years in Varanasi

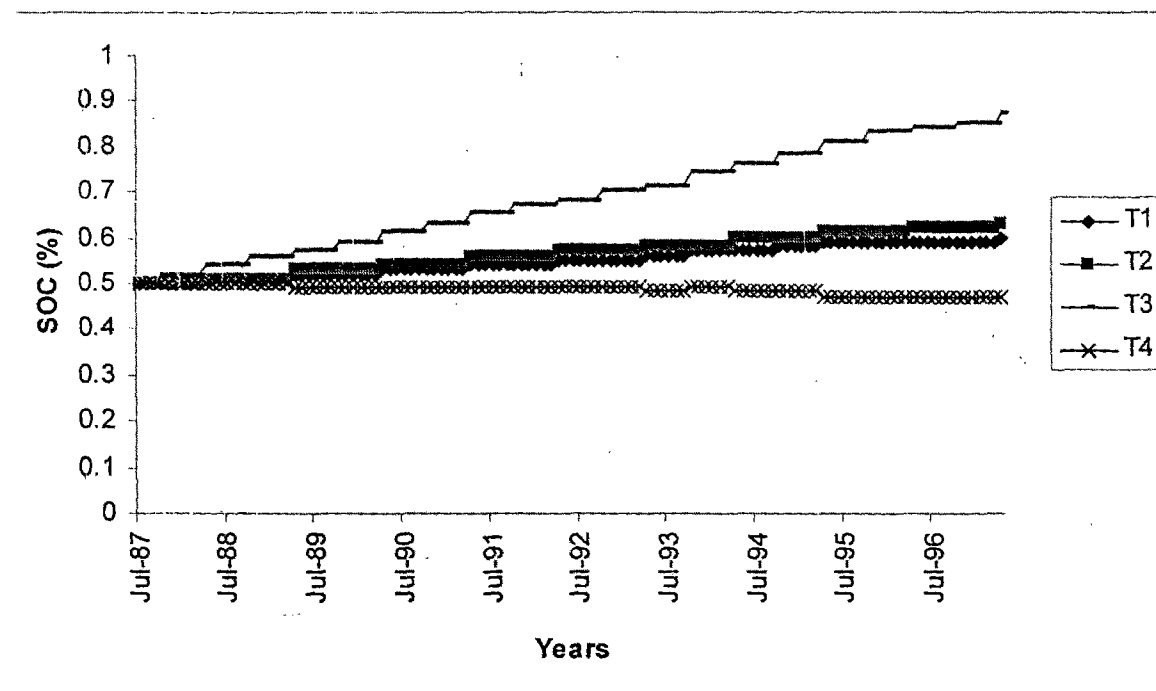


Fig. 35 Changes in soil organic carbon over different years in Varanasi

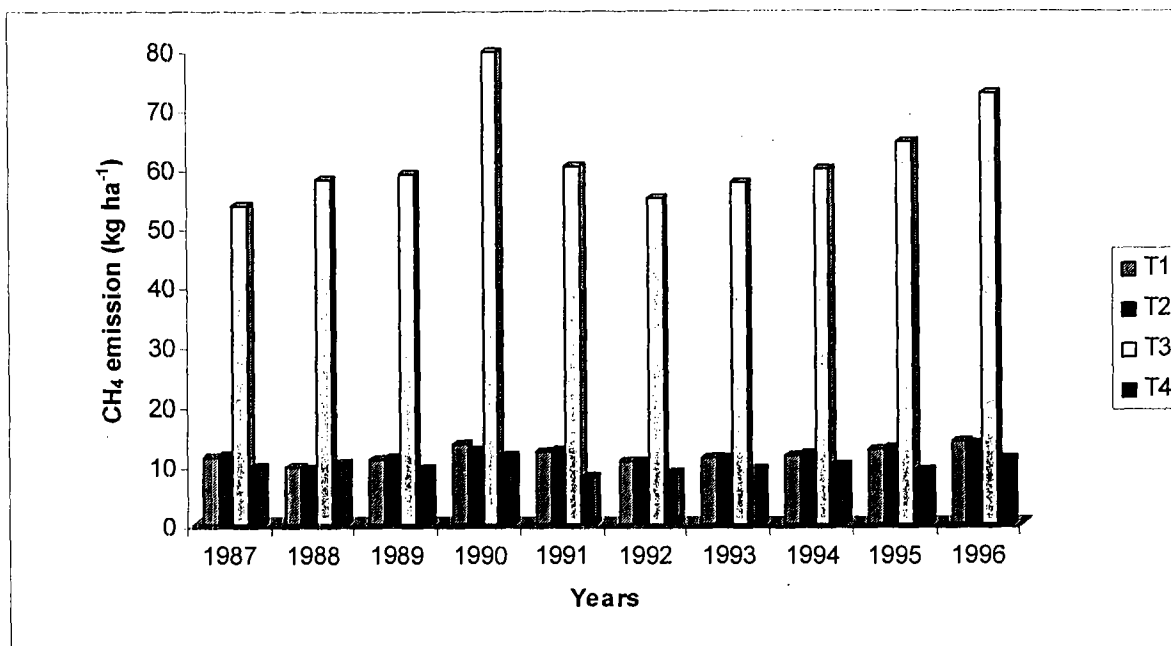


Fig. 36 CH₄ emission from rice field in different years in Varanasi

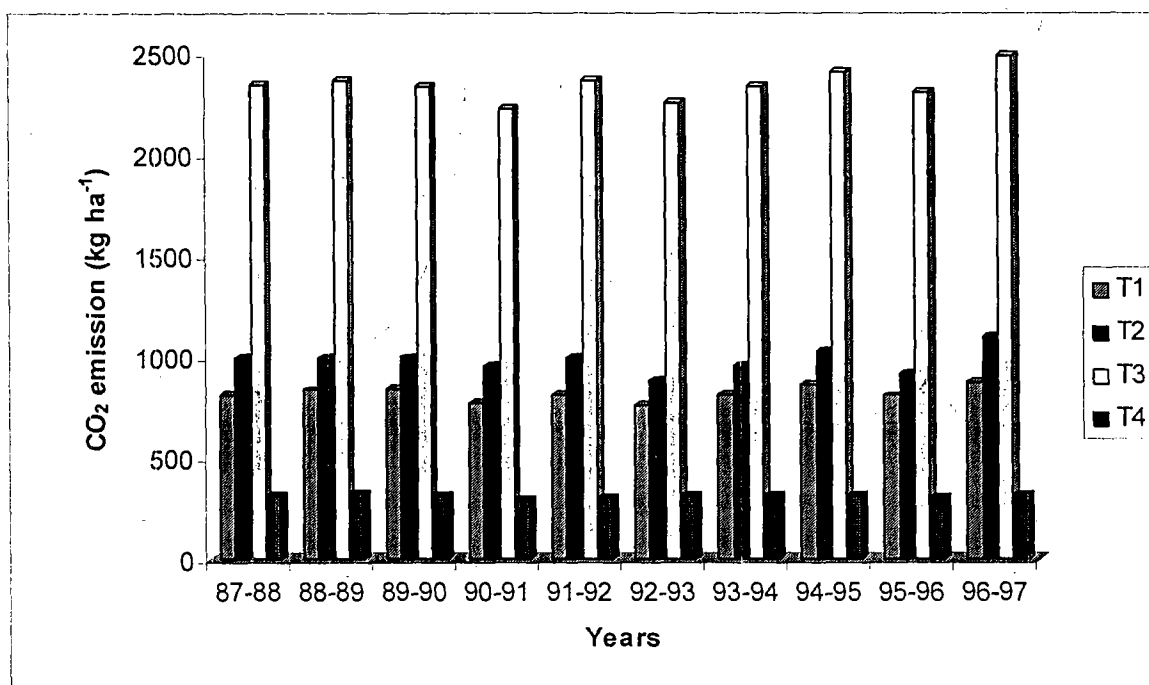


Fig. 37 CO₂ emission from rice wheat field in different years in Varanasi

radiation. Control treatment showed stable yield over the years. However, in both T2 and T3 treatments yield came down to 9.3 tonnes ha⁻¹ from 11 tonnes ha⁻¹ (Fig. 38). It decreased significantly to the extent of 0.17 t ha⁻¹ year⁻¹.

Initial soil organic carbon at this site was much higher (0.94%) compared to all other sites. Here, this remained unchanged in blank, control as well as 100% NPK plots. Continuous application of FYM (T3) increased SOC slightly from 0.94% to 1.15% over the period of ten years (Fig. 39) unlike other sites where the increase was much larger.

Methane and CO₂ emissions followed a similar trend with treatment as in other stations but the amounts were very different. There was much greater emissions of methane from the soils here and much less of CO₂ relative to other locations (Fig. 40 and 41).

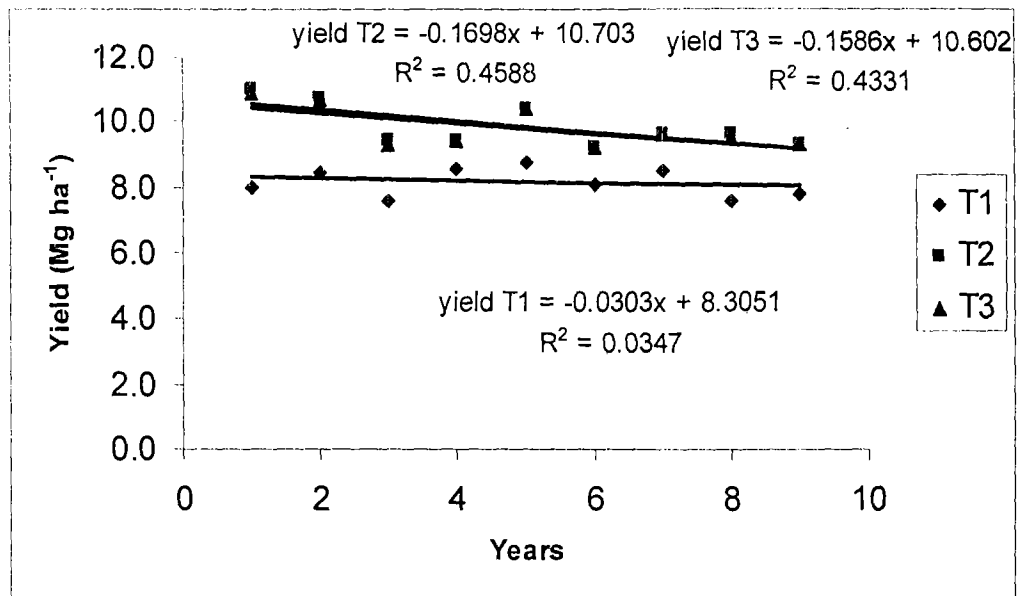


Fig. 38 Rice wheat yield over different years in Calcutta

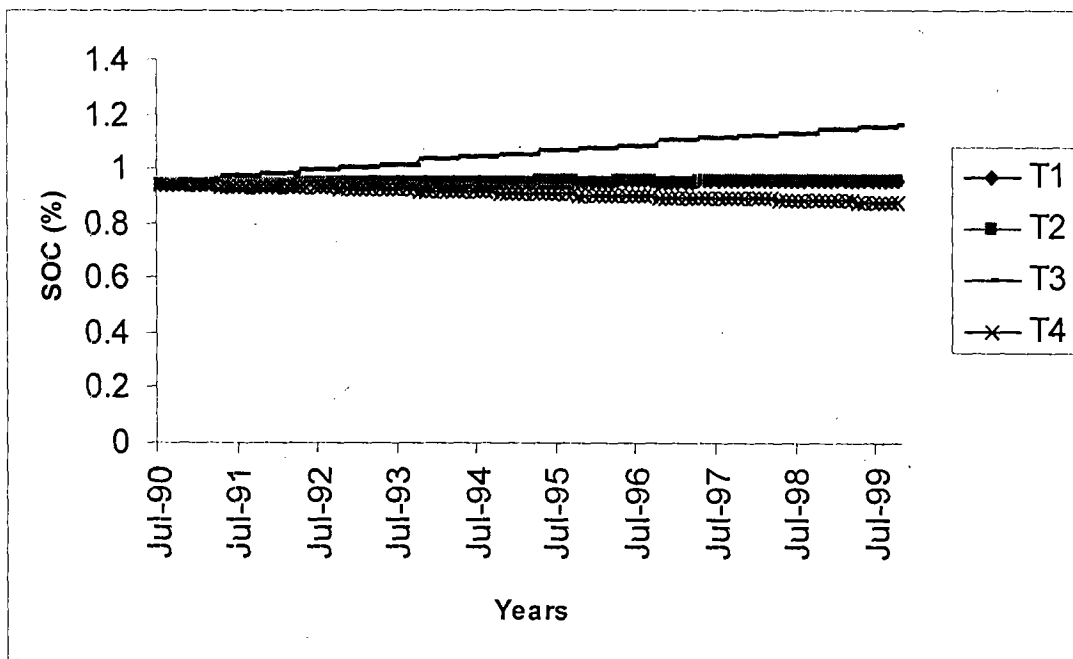


Fig. 39 Changes in soil organic carbon over different years in Calcutta

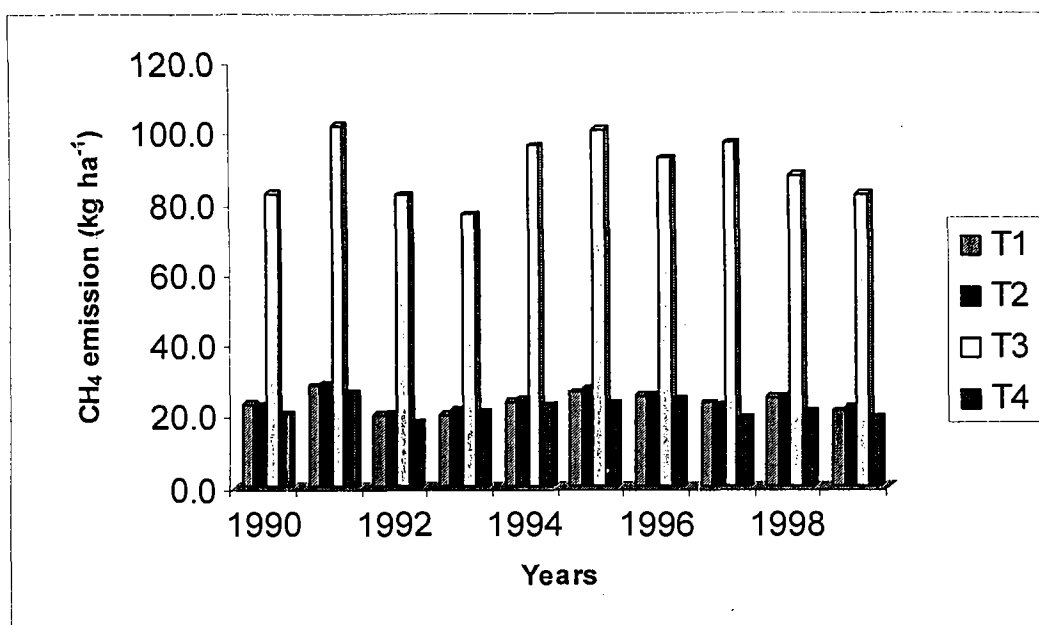


Fig. 40 CH₄ emission from rice field in different years in Calcutta

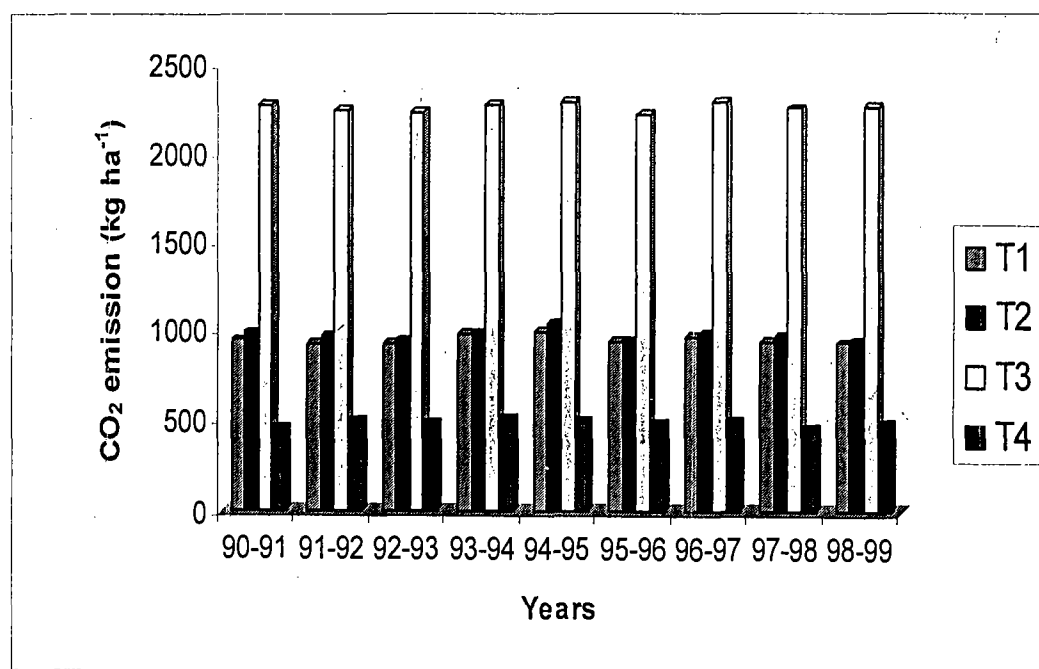


Fig. 41 CO₂ emission from rice wheat field in different years in Calcutta

Summary and Conclusion

Carbon is found in all living organisms and is the major building block for life on earth. It exists in many forms, predominantly as plant biomass, soil organic matter and as the gas CO_2 in the atmosphere and dissolved in seawater. Carbon cycle holds centre stage in global change studies due to its role in influencing weather and determining food, fibre and wood supply for human use through plant productivity. Over the past 150 years the amount of carbon in the atmosphere has increased by 30%. Increase in CO_2 concentration is resulting in warming of earth's temperature. Although agriculture is not a large emitter of GHGs, it can assist in reducing the overall carbon emissions by sequestering this in large area of land. The soil constitutes a significant reservoir of carbon in both mineral and organic forms. The soil organic carbon pool is about 2.1 times that of the atmosphere pool and about 2.7 times that of the biotic pool comprising land plants.

Rice-wheat production systems occupy 24 million ha of cultivated land in the Asian subtropics. The system has been responsible for providing livelihood security to millions of people in the Indo-Gangetic plains (IGP). However, off-late there are reports that the productivity of the system is declining and decrease on soil organic matter could be a possible cause for this. Adoption of intensive agriculture in IGP is also believed to have contributed significantly to emission of greenhouse gases like CO_2 , CH_4 and N_2O . The need to manage soil organic carbon

is clear for sustainability of the agro-ecosystem. It will be necessary to develop strategies that not only halt the degradation of environment but, in time, also reverse it. We need to identify such carbon management strategies that may anyway be needed for sustainable development of agriculture. Enhancing organic matter content of our soils will, for example, ensure better soil fertility as well as assist in sequestering atmospheric carbon.

In view of its importance, several studies have earlier focused on studying the carbon dynamics in rice-wheat systems. Most studies have focused on quantifying the above ground carbon dynamics in terms of yield trends from the system and in understanding the principal causes of the trends. Although there are also reports that soil organic carbon is declining in these systems much work needs to be done to clearly understand the soil carbon dynamics. This would, however, require long-term assessment of the effects of different land use management strategies on food production as well as soil organic carbon in different regions. Conventional field experiments in critical regions are best suited but can be very time consuming for assessing the long-term effects. Dynamic simulation models of crop growth are alternate tools that can be used to supplement field research and to determine the long-term consequences of agricultural management on carbon dynamics.

The study reported in this thesis, therefore, employs field experiments, historical databases, as well as simulation models to understand the carbon dynamics in the rice-wheat systems of the Indo-Gangetic plains. The specific objectives of the study were too

1. To study carbon dynamics in rice-wheat cropping system in field.
2. To test a model for studying carbon dynamics in rice-wheat cropping system.
3. To extrapolate the results of rice-wheat system to other sites in the Indo-Gangetic plains.

The field experiment was conducted in the IARI farm for two years in rice-wheat cropping system. The experiments were laid out in a split plot design in rice. The main plots comprise of two tillage treatments viz. puddled and non-puddled. The subplots included 7 fertilizer treatments. Soil organic carbon and soil microbial biomass carbon was monitored in plots fertilized with recommended doses of urea (120 kg N ha^{-1}), urea plus FYM, urea plus green manure, totally organic sources and urea plus crop residues. Blank plot was also kept for studying changes in soil organic carbon in bare soil. Soil samples from 0-15 and 15-30 cm soil layer were collected from each plot at different crop growth stages. Soil microbial biomass carbon was estimated using chloroform fumigation extraction method.

The InfoCrop model, earlier calibrated and validated by some authors for rice-wheat system has been used for this study. A brief soil carbon module was

developed and included in InfoCrop based on our field experiment and literature review. This model was calibrated with the data from independent rice-wheat field experiments conducted earlier in IARI farm for two years (1999-2001). Besides this, data from a long-term experiment (1985-1997) done earlier in the Indo-Gangetic plains was also used to validate the model. This experiment was conducted in rice-wheat system at the experimental farm of PAU, Ludhiana was used to validate the performance of the model. The validated model for carbon dynamics was used to study long-term soil carbon dynamics of the rice-wheat system at representative locations in the Indo-Gangetic plain. The locations selected were Delhi, Karnal, Varanasi and Calcutta. Long-term change in yield, soil organic carbon, methane emission and CO₂ emission were simulated for these representative stations.

The following are the main conclusions from this study:

1. Application of organic matter in different forms to rice-wheat system in the north-western Indo-Gangetic plains results in increased soil organic carbon of 0-15 cm soil in field experiments. Crop residue treatment showed significantly higher values of soil organic carbon during the second year in both rice and wheat crop. In most cases lower soil layers showed no significant change in soil organic carbon when organic matter was added as surface application.

2. Puddling of soil in rice crop results in higher soil organic carbon than **nonpuddled one**. In 2002 rice crop puddled treatments showed (12-16) % more organic carbon content than non-puddled one in 0-15 cm soil layer while in 15-30 cm soil layer this value is (15-20) %. Puddling creates anaerobic conditions in field, which slows the decomposition of organic matter, reduced the loss of carbon as CO₂ and led to higher organic carbon content of soil.
3. Application of organic matter also affects soil microbial biomass carbon (MBC). Blank plot showed significantly less microbial biomass carbon than fertilized plots. Very high values were observed in FYM, green manure and totally organically amended plots. Maximum value of MBC (232.6 mg kg⁻¹) was noted in the FYM treatment in the second rice crop. Fertilizer or manure treatment did not affect MBC of 15-30 cm soil. Puddling significantly increases the microbial biomass carbon of soil in both rice and wheat crop.
4. Soil microbial biomass carbon reaches its peak during the flowering stage of the crop in both rice and wheat. This may be associated with the declining root activity after flowering. The decrease in microbial biomass carbon thereafter may also be due to a shift in the composition of the microflora of the soil.
5. Microbial biomass carbon is linearly related to soil organic carbon in both rice and wheat. When direct measurement of MBC is not possible, this soil organic carbon dependant linear relationship could be used to estimate its value.

6. InfoCrop model simulates biomass, grain yield, CH₄ emission and CO₂ emission reasonably well for the short-term rice-wheat field experiment in different treatments of organic and inorganic fertilization. However, model overestimated CH₄ emissions for the treatment where FYM was added. In the wheat experiment of 2000 the model was able to reasonably simulate the grain as well as biomass yield in all treatments. But the simulated CO₂ emissions were 10-20% less than the measured values in different treatments. In the rice experiment of 2000 the model showed very accurate results for CO₂ emissions for all treatments.
7. For the long-term experiment conducted in Ludhiana, simulated grain yields were not necessarily similar to the measured yields in different years. This could be partly due to inadequate calibration of the model due to limited measured data. But the trends in simulated rice-wheat yields were more or less similar to the measured trends in all treatments, indicating models relative capability to simulate long-term changes once properly calibrated.
8. In the same experiment, 50% NPK + green manure treatment in rice, simulated values of organic carbon increased from 0.4% to 0.55% over the years while in 50% NPK + FYM treatment it increased from 0.4% to 0.59%. The InfoCrop was able to simulate this increasing trend. In wheat crop also model accurately simulated soil organic carbon and the observed and

simulated values are very much similar. In 50% NPK + FYM and 50% NPK + green manure treatment both observed and simulated values of SOC were same indicating that InfoCrop is capable of satisfactorily simulating the carbon dynamics, especially soil organic carbon in rice-wheat systems. It can also handle the effects of different organic and inorganic nitrogen management strategies as well as the effects of weather and irrigation management. Further improvement in the model may be needed to correctly estimate greenhouse gases emissions.

9. The simulated results showed that the SOC does not decrease in rice-wheat systems under different types of managements and locations. For the locations studied, there was either no increase or a small increase in SOC when no crops were not fertilised. Addition of only inorganic or organic fertilisers or their mixtures every year to rice-wheat systems always resulted in considerable increase in SOC. The magnitude of increase was much small in eastern regions where the initial SOC as well as ambient temperatures were higher. In view of the contradictory reports of long-term changes in SOC in literature, more detailed evaluation of the model may, however, be desirable.
10. Addition of organic fertilisation always resulted in very large increase in greenhouse gases emissions. The trade-off between increased soil carbon sequestration versus carbon emissions needs further quantification.

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* Original not seen

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