

**CHANGES IN SOIL PHYSICAL PROPERTIES  
AND CROP YIELDS WITH LONG-TERM  
ADDITIONS OF *Lantana camara*  
BIOMASS IN RICE-WHEAT  
CROPPING**

**THESIS**

*By*

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*Submitted to*



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**IN**

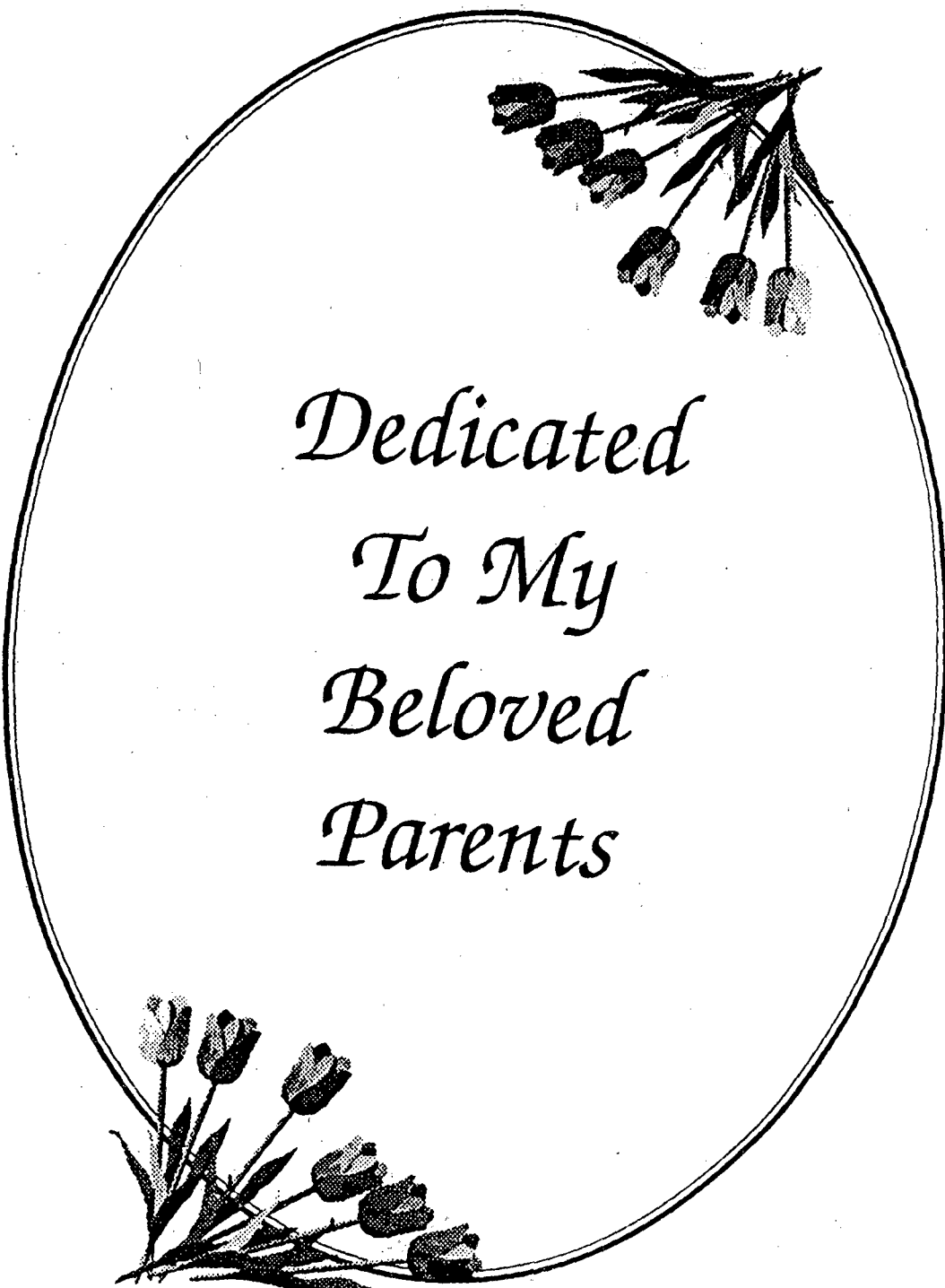
**Partial fulfilment of the requirements for the degree**

**OF**

**DOCTOR OF PHILOSOPHY IN AGRICULTURE  
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*Dedicated  
To My  
Beloved  
Parents*




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### **CERTIFICATE I**

This is to certify that the thesis entitled "**Changes in Soil Physical Properties and Crop Yields with Long-term Additions of *Lantana camara* in Rice-Wheat Cropping**" submitted in partial fulfilment of the requirements for the award of the degree of Doctor of Science (Agriculture) in the subject of Soil Science of Himachal Pradesh Krishi Vishvavidyalaya, Palampur is the bonafide research work carried out by Mr. Lav Bhushan (A-95-40-08) son of Shri. Bipan Chand Sood under my supervision and that no part of this thesis has been submitted for any other degree or diploma.

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

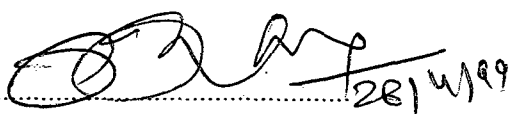
  
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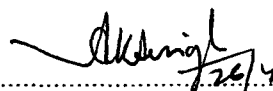
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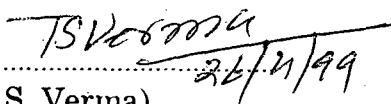
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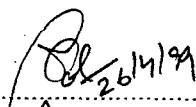
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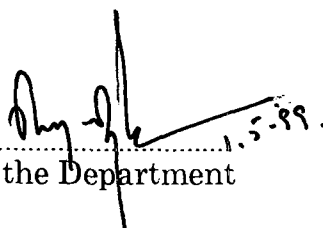
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*I owe entire responsibility for all the errors and omissions.*

Place : Palampur

Dated : the December 29, 1998



(Lav Bhushan)

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## LIST OF ABBREVIATIONS AND NOTATIONS

Abbreviation / Notation	Full form
ASV	apparent specific volume
BGA	blue green algae
CBS	clod breaking strength
cm	centimetre
COLE	coefficient of linear extensibility
CT	cumulative time
DAS	days after sowing
DAT	days after transplanting
$\Delta$ ASV	change in apparent specific volume
dia	diameter
eqn.	equation(s)
<i>et al.</i>	and others
FC	field capacity
Fig.	figure(s)
FYM	farm yard manure
GJ	Gega Jules
ha	hectare(s)
kPa	kilo Pascal
LL	liquid limit
LSD	least square difference
min	minute(s)
mm	milli meter
MPa	Mega Pascal
MWD	mean weight diameter
NLWR	non-limiting water range
OC	organic carbon
OM	organic matter
PAWC	plant-available water capacity
PI	plasticity index
PL	plastic limit
pp.	pages
PU	prilled urea
PWP	permanent wilting point
RMD	root mass density
SL	shrinkage limit
SPR	soil penetration resistance
USG	urea super granules
viz.	namely

WHC	water holding capacity
WSA	water stable aggregates
%	per cent
$\mu$ m	micro-meter
$\Gamma$	surface tension
$\theta$	volumetric water content
$\rho_b$	bulk density
$\Psi_m$	matric suction
$\rho_s$	particle density
$\rho$	density
@	at the rate of
$f$	porosity
$f_a$	air-filled porosity
$I$	cumulative infiltration
$i$	infiltration rate
i.e.	that is
K	potassium
$K_s$	saturated hydraulic conductivity
m	meter
Mg	Mega gram
N	nitrogen
p.	page
P	phosphorus
r	correlation coefficient
s	second
w	gravimetric water content

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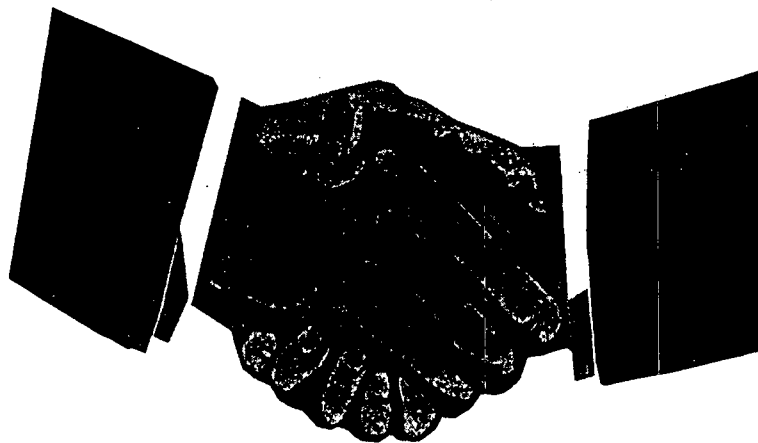
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# INTRODUCTION

# I INTRODUCTION

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The rice-wheat cropping system dominates agricultural system in Northern parts of country with an approximate area of 10.5 m hectares (Singh, 1995). The rice-wheat cropping system is pivotal to food security system not only of the country but of Indian subcontinent as a whole. The ten-fold increase in rice-wheat cropping system in India, Bangladesh, Nepal and Pakistan during the last 30 years is an ample proof of it (IRRI, 1992). About half of the irrigated wheat production in South Asia comes from rice-wheat rotation (Pillai, 1994).

The requirements of growing environment for rice and wheat crops are contrastingly different. While rice grows best under water stagnant conditions, wheat requires a well pulverised soil with a proper balance of moisture, air and thermal regime. Rice in most parts of South and South-east Asia is traditionally transplanted in well puddled soils. In Himachal Pradesh rice is cultivated with wet tillage in 70 per cent of total rice area. Puddling is an intensive tillage system which brings about significant changes, especially, in physical properties of soil, including structural, hydraulic and mechanical properties. Such changes, although are favourable for rice, are not suitable for the following wheat crop. Consequently, wheat performs poor in post-rice soils.

Wheat yields after rice have generally been observed to be lower than yields after upland crops like, maize, soybean etc. Several reasons have been assigned to the low productivity of wheat in post-rice soils, although there is lack of systematic studies comparing wheat yields in rice and non-rice soils under similar environments. Of late, serious and concerted efforts are being made at national and international level to identify constraints to wheat cultivation in rice soils. Scientists of International Rice Research Institute (IRRI), International Centre for Maize

and Wheat Improvement (CIMMYT) and National Agricultural Research System (NARS) are investigating soil productivity under rice-wheat cropping system. Diagnostic surveys conducted throughout the rice-wheat zone in South Asia over the last 5 or more years have identified soil and water degradation, and nutrient deficiency as the key constraints affecting wheat productivity after rice (Hobbs, 1994). Rice soils, generally, have high penetration resistance in the root-zone, compact surface layers which are difficult to till into well pulverised seed bed, and have restricted drainage resulting into occasional water stagnation and aeration problem. The management practices to ameliorate ill-effects on wheat due to unfavourable soil physical conditions are problem and site specific.

Incorporation of organic residues have long been known to improve physical and chemical properties of puddled soils and, thus the crop yields. But the challenge always has been to obtain organic material in sufficient quantities for incorporation into soils, because most of the organic materials have alternate uses as fodder or fuel or both. It was thought to use locally available organic residues as organic amendment, which have few alternate uses. In North India, *Lantana camara* is a fast growing bush and is encroaching on the cultivated lands at an alarming rate. It is an obnoxious weed and unfit for cattle feed. Being a thorny bush, it is rarely used as fuel wood. Serious efforts are being made in the state to eradicate this weed. It has its maximum growth and foliage during wet season (June-September), when rice is cultivated. A long-term field experiment was initiated in June, 1987 to study the potential of lantana biomass as an organic amendment in rice-wheat cropping. Changes in chemical properties due to lantana additions in this experiment have been extensively studied (Sharma,

1996; Sharad, 1997). The present study proposed to investigate changes in soil physical properties during the tenth cropping cycle and their effects on crop productivity.

The characterisation of soil physical environment in relation to plant growth is difficult because of strong interdependence of different soil physical properties. It is difficult to change one soil physical property without changing the other one. Letey (1985) proposed 'Non-Limiting Water Range' (NLWR) as a single value soil physical index. The index requires extensive field testing to establish its utility in characterising soil physical environment in relation to plant growth.

The objectives of the present study were to investigate :

1. the organic carbon build-up in 0-0.30 m soil layer as a result of lantana additions;
2. changes in soil structural properties, viz. bulk density, porosity, pore-size distribution, air-filled porosity at field moisture content, water-stability of aggregates, apparent specific volume, puddlability, coefficient of linear extensibility, surface cracking behaviour clod-size distribution and mechanical impedance;
3. changes in soil hydraulic properties, viz. soil-water retention characteristics, plant-available water capacity, saturated hydraulic conductivity, infiltration characteristics and soil-water contact angle;
4. changes in soil mechanical properties, viz. soil consistency limits, draft requirement and clod breaking strength;
5. rooting pattern of wheat in relation to changes in soil physical properties due to lantana additions;
6. direct and residual effects of lantana additions on rice and wheat yield; and
7. the characterisation of soil physical environment in terms of "Non-Limiting Water Range", a single value index and its relation with wheat yield.



**REVIEW  
OF  
LITERATURE**

## **II REVIEW OF LITERATURE**

---

Deterioration in soil physical properties due to puddling is considered to be the major cause of reduction in the productivity of upland crops after lowland rice. It is well known that a general relationship exists between soil physical properties and the amount of organic matter (OM) in a soil. All other factors being equal, a soil with a high soil OM has good physical conditions. Thus, a treatment capable of increasing the soil OM level is expected to improve physical conditions of soil.

Information on the role of various organic amendments in improving OM content and physical conditions of soils, with consequent effect on crop productivity, under rice-wheat cropping, have been compiled in this chapter. The literature has been reviewed under the following heads :

### **2.1 Effect of Organic Matter on Soil Physical Properties**

#### **2.1.1 Soil Aggregation**

#### **2.1.2 Bulk Density**

#### **2.1.3 Moisture Content and Availability**

#### **2.1.4 Water Movement**

### **2.2 Effect of Organic Residues on Soil Organic Matter**

### **2.3 Effect of Organic Residues on Soil Physical Properties**

#### **2.3.1 Soil Structural Properties**

##### **a) Soil Aggregation**

##### **b) Bulk Density**

##### **c) Porosity**

##### **d) Soil Penetration Resistance**

##### **e) Other Structural Properties**

### 2.3.2 Soil Hydraulic Properties

- a) Water Retention and Availability
- b) Infiltration
- c) Hydraulic Conductivity
- d) Soil-Water Contact Angle

### 2.3.3 Soil Mechanical Properties

- a) Soil Consistency Limits
- b) Energy Required for Land Preparation
- c) Clod Breaking Strength

## 2.4 Effect of Organic Materials on Crop Yields in Rice-Wheat Sequence

## 2.5 Research Gaps

## **2.1 Effect of Organic Matter on Soil Physical Properties**

All physical properties of soil are affected by changes in OM levels of soil. The extent to which soil physical properties might change and conditions under which the improvement in these parameters might occur are poorly defined. In the following para, an attempt has been made to briefly explain the mechanism by which the OM affects soil physical properties.

### **2.1.1 Aggregation**

Martin *et al.* (1955) defined a soil aggregate as a “naturally occurring cluster or group of soil particles in which the forces holding the particles together are much stronger than the forces between adjacent aggregates.” Different forces are involved in aggregate formation and their stabilisation. Few agents are involved in both processes.

Organic matter affects, both, formation and stabilisation of aggregates; the later being affected more. Baver (1935) concluded that OM favoured formation of relatively large stable

aggregates (>0.1 mm dia). Significant effect of OM content on aggregation was observed in soil having clay content < 25 per cent; aggregation also improved with OM in soil having clay content  $\geq$  35 per cent, but not to the same extent. In fine-textured soils, coarse organic materials may prevent the formation of large aggregates by blocking attractive forces between smaller aggregates.

Organic colloids in combination with clay, forming clay-organic complexes, are responsible for soil aggregation. Greenland (1965) reviewed the results of various investigators and concluded that about 52-98 per cent of the total carbon in soil existed in clay-carbon complexes.

In temperate soils, OM is the primary aggregate stabilising agent. The incorporation of OM in soil increases microbial activities of fungi, actinomycetes, bacteria and yeast. Fungi and actinomycetes produce mycelia. The metabolic processes of the micro-organisms synthesise complex organic molecules. Decomposition products of plant and animal residues, like microbial gums and mucilaginous, low molecular weight fluvic acid molecules, and linear organic polymers like fats and waxes, are responsible for aggregate stabilisation (Greenland *et al.*, 1962; Harris *et al.*, 1966; Allison, 1973).

Greenland (1965), however, argued that OM determination may not always correlate well with soil aggregation because the total OM analysis is not measuring just those OM fractions responsible for aggregate stabilisation. De Kimpe *et al.* (1982) did not find significant correlation between soil OM levels and dry- and wet-sieve analysis in their study of 21 Quebec soils. Cootie and Ramsey (1983) did not find a significant correlation between OM and mean weight diameter in four Ontario soils. Harris *et al.* (1966) observed that poor correlation

between OM content and soil aggregation may also result from inadequacies of sieving procedures.

### 2.1.2 Bulk Density

With few exceptions, if any, OM decreases the bulk density of soils. It may result from the improvement in soil aggregation and/or by dilution of soil matrix with less dense material. Many studies have reported significant and negative correlation between OM content and bulk density of soils (Curtis and Post, 1964; Saini, 1966; Soane, 1975; Millette *et al.*, 1980; De Kimpe *et al.*, 1982; Coote and Ramsey 1983; Sharma and Aggarwal, 1984; Sharma *et al.*, 1995)

### 2.1.3 Moisture Content and Availability

Water holding capacity (WHC) of soils depends principally on (i) the amount and size distribution of soil pores, and (ii) the specific surface area of soils. Pore-size distribution affects WHC mainly at higher water potentials, such as those at field capacity, where WHC is a function of soil structure. At lower water potentials close to permanent wilting point, the WHC is a function of soil texture, and depends on the specific surface area of soil particles. Organic matter affects both the soil properties. It increases soil pores favourable for water retention and the specific surface area of soils. Water holding capacity of OM itself is very high, although much of the water is retained at potentials below permanent wilting point (Feustal and Byers, 1936; Jamison, 1953). Thus, when added to soil, it dilutes the material of low water retentivity with that of high retentivity.

Organic matter increases aggregation and decreases bulk density of soils (Biswas *et al.*, 1971; Khaleel *et al.*, 1981; De Datta and Hundal, 1984; Sharma and Aggarwal, 1984; MacRae

and Mehuys, 1985; Clapp *et al.*, 1986). It increases total porosity and causes alteration in the pore-size distribution; the relative number of water retention pores increases. It is especially true in coarse-textured soils (Volk and Uttery, 1973). Increase in WHC at lower water potentials due to increase in specific surface area of soils upon addition of OM has also been reported by various workers (Volk and Uttery, 1973; Gupta *et al.*, 1977; Rajput and Sastry, 1988a). Niskanen and Mantylahti (1987), using the data from 60 soils, obtained the following relationship ( $r^2 = 0.84$ ) between specific surface area ( $\text{m}^2 \text{g}^{-2}$ ), clay (per cent) and organic carbon content (OC, per cent) of soils :

$$\text{Specific surface area} = 2.69 + 1.23 \text{ clay} + 8.69 \text{ OC} \quad (2.1)$$

Equation (2.1) shows that the effect of OC on specific surface area is about 7 times that of clay content.

Khaleel *et al.* (1981) concluded that about 80 per cent of the observed variations in percentage increase in water retention may be explained by soil texture and increases in organic carbon. Coarse-textured soils, in general, show greatest increase in water retention at, both, field capacity and permanent wilting point due to addition of organic matter (Clapp *et al.*, 1986).

Unlike WHC, the plant-available water capacity (PAWC), i.e. the water retained between field capacity and wilting point, is affected little or not at all by OM. It is because OM raises water retention of soils at both lower and higher tensions, and decreases their bulk density. The decreased bulk density tends to counter-balance any increase in PAWC on mass basis. So, when moisture content is computed on volume basis, increase may not be as dramatic or even non-existent (Khaleel *et al.*, 1981; MacRae and Mehuys, 1985; Clapp *et al.*, 1986).

Most of the studies which show positive correlation between PAWC and OM of soils have computed water content on mass basis (Biswas and Ali, 1969; Epstein *et al.*, 1976; Gupta and Larson, 1979; Lal, 1979 ; De Kimpe *et al.*, 1982). In order to evaluate the real effects of OM on PAWC, the moisture should be determined on volume basis.

Diverse opinions have emerged regarding the effect of OM on PAWC in relation to soil texture. According to one group of workers, OM benefits PAWC in coarse-textured soils only. Jamison (1953), using the data of Peele *et al.* (1948), concluded that OM increased PAWC of sandy soils having clay < 15 per cent. As soil texture became finer, OM had less effect on PAWC; factors other than OM dominate in determining the PAWC. In another study, Jamison and Kroth (1958) found OM to influence PAWC only in soils of medium-low clay content (13-20 per cent). Earlier, Coile (1938) had also concluded that OM increased moisture equivalent in coarse-textured soil more than their permanent wilting point, and the effect on water retention, in general, decreased with the fineness of texture. Several other studies have reported increase in PAWC (on volume basis) with the increase in OM content of sandy soils (Salter *et al.*, 1965; Biswas *et al.*, 1971 Kumar *et al.*, 1984; Bhadoria, 1987; MacRae and Mehuys, 1987; Ramunni *et al.*, 1987; Rajput and Sastri, 1988a,b; Tester, 1990). But contrary to this, many workers did not find any improvement in PAWC of sandy soils due to additions of OM (Petersen *et al.*, 1968; Hartmann and De Boodt, 1974; Singh *et al.*, 1976; Kladvko and Nelson, 1979).

According to another school of thought, it is the fine-textured soils which benefit most from OM additions for their PAWC (Khaleel *et al.*, 1981; Clapp *et al.*, 1986). These reviews conclude that in fine-textured soils, increases in water retention due to increase in OM are greater at field capacity than wilting point. This effect is probably the result of increased

aggregation, producing a greater number of large-size pores which could not drain under gravity. In coarse-textured soils, on the other hand, OM produces a large increase in water retention at permanent wilting point than at field capacity, perhaps due to an increase in the number of smaller pores not draining at  $-1500$  kPa. Consequently, PAWC increased in fine-textured and not in coarse-textured soils due to OM build-up. Russel *et al.* (1952) reported about  $0.012 \text{ cm}^3 \text{ cm}^{-3}$  increase in PAWC of a silty loam soil due to addition of  $40 \text{ Mg ha}^{-1}$  manure. However, Petersen *et al.* (1968), Morachan *et al.* (1972), Epstein (1975) and Weil and Kroontje (1979) did not find any improvement in PAWC due to OM in silt loam to clay loam soils. Sommerfeldt and Chang, (1986) rather observed a decline in PAWC with the increase in OM content of a clay loam soil.

Many workers have reported improvement in PAWC due to OM irrespective of soil texture. Unger (1975) observed increase in PAWC by about 1.8 per cent (volume basis) for each per cent increase in OM for soils ranging in texture from sandy to clay. Mbagwu (1989) also obtained increased PAWC with manure applications (2-10 per cent) in sandy loam, sandy clay loam and clay soils; the effect, however, decreased with the fineness of texture. Studies reveal that the influence of OM on WHC is comparatively more at lower than at higher tensions, irrespective of soil texture (Salter and Williams, 1963; Biswas and Ali, 1969; Biswas *et al.*, 1971; Sharma and Nath, 1979; Jo, 1990). On the bases of data from 144 rice soils, Jo (1990) concluded that every 1 per cent increase in OM increased field capacity and PWP by 2.21 and 1.01 (w/w), respectively. Water retention is largely affected by the clay content of soils (Biswas and Ali, 1967).

Such diverse conclusions may arise due to varied nature of soil OM, different sources of organic amendments used, different duration of OM additions after which the data were collected, and different ecological situations under which the experiments were conducted. Same OM content in soils may yield different results depending on whether the OM was directly incorporated into soil or was build-up *in situ* over a period of time (Biswas and Ali, 1969).

#### 2.1.4 Water Movement

Water transmission characteristics of soils are closely associated with their OM status (Wischmeier and Mannering, 1965; Allison, 1973; Khaleel *et al.*, 1981; Jo, 1990). In general, while fine-textured soils show increase in infiltrability and saturated hydraulic conductivity with the increase in their OM content due to improvement in aggregation (Tiark *et al.*, 1974; Gupta *et al.*, 1977; Mathers and Stewart, 1984), sandy soils show a decline (Das *et al.*, 1966; Biswas *et al.*, 1971; Kumar *et al.*, 1984; MacRae and Mehuys, 1987; Rajput and Sasrty, 1988a; Bhagat and Acharya, 1989; Bhagat, 1990). The decline is associated with reduction in water transmission and increase in water retention pores of soils. If the OM is hydrophobic in nature, whatever the soil texture, it would decrease the hydraulic conductivity of soils (Weil and Kroontje, 1979). Gupta *et al.* (1977) observed decline in the diffusivity of a sandy soil with the increase in OM content. They argued that this behaviour of sandy soils is important with respect to water storage, particularly in wet tropics and arid zones. Lower unsaturated hydraulic conductivity and diffusivity decrease the water loss due to evaporation.

## 2.2 Effect of Organic Residues on Soil Organic Matter Levels

The maintenance or accumulation of OM in soil is dependent on a number of factors, such as the chemical nature (composition, moisture content, C : N ratio, mineral ion content ), amount, timing, method and frequency of added material, soil (topography, soil type, texture, soil temperature, pH, moisture, native OM content, microbial activities, use of fertilisers etc.) and climatic factors (solar radiation, precipitation, evaporation ). The popular conclusion is that a plant material resistant to ready decomposition is necessary if soil OM level is to be maintained or increased. Warman (1980) stated that plant materials typically low in N (< 1.5 per cent N on dry-weight basis) can be effective in improving the OM content of soil.

Different types of organic materials that can be used are farm yard manure (FYM), animal wastes, crop residues, green manures, composts, night soil, sewage, sludge and organic wastes from industries etc. Asian farmers mostly use cattle dung as the organic source; composts and green manures are also common.

The decomposition rate of these materials in soil depends on (i) the chemical composition (C:N ratio) of material, (ii) soil temperature, (iii) soil moisture, (iv) method of application (surface applied, soil incorporation etc.), and (v) rate of application. Organic materials added to soil practically burn-up in humid tropics and sub tropics (Singh, 1962). Decomposition is slower in waterlogged than in aerable upland soils. Wetting and drying processes, as in rainfed lowland rice, speed-up the rate of decomposition (Amato *et al.*, 1984). Sometimes additions of fresh OM to soil accelerate the decomposition of native OM, rather than a build-up (Singh, 1962; Khaleel *et al.*, 1981 ). Therefore, moderate application of organic

residue have negligible residual long-term effect on soil OM content. For the build-up and maintenance of organic materials, regular additions of large quantities of organic materials are required (Khaleel *et al.*, 1981; Eck and Unger, 1985; MacRae and Mehuys, 1985). Also, substantial increase in OM content is required for perceptible change in soil physical properties.

Biswas *et al.* (1970) observed increase in the organic carbon (OC) content from 0.46 to 0.61 per cent with the annual additions of FYM @ equivalent to 45 kg N ha<sup>-1</sup> ( $\cong$  9.0 Mg ha<sup>-1</sup>) for 10 years in a sandy loam soil at Bhubneshwar (Orissa). The increase in OC was 33 per cent over control. Low and Piper (1973) also observed 33 per cent increase in OM content in a loam soil, with the application of FYM @ 75 Mg ha<sup>-1</sup> for 6 consecutive years. The OM increased from 3.0 in control to 4.0 per cent in treated soil. Formoli and Prasad (1979) also observed increase in OC with the application of 15 Mg ha<sup>-1</sup> FYM for 3 years in a sandy clay loam soil. Ganai and Singh (1988) reported 29 per cent increase in OC from 0.72 to 0.93 per cent with the use of FYM @ 20 Mg ha<sup>-1</sup> for 2 years at Malan (H.P.). At Pantnagar, Kumar and Tripathi (1990) reported 15 per cent increase in OM, from 2.50 in control to 2.88 per cent, with the use of FYM @ 15 Mg ha<sup>-1</sup> for 9 years in a silty clay loam soil. More (1994) reported an increase of 30 per cent in OC (from 0.50 in control to 0.65 per cent) with the incorporation of FYM @ 50 Mg ha<sup>-1</sup> in a sodic Vertic fine-textured soil at Parbhani (Maharashtra). According to Gupta *et al.* (1995), use of FYM @ 10 Mg ha<sup>-1</sup>, along with either prilled urea or urea super granules, increased the OC by 27 and 20 per cent over control at Sabour. The OC content increased from 0.41 in control to 0.52 and 0.50 per cent for the two urea forms, respectively.

Gupta *et al.* (1995) reported significant increase in OC from 0.39 to 0.43 per cent with the use of 5.2 Mg ha<sup>-1</sup> of rice husk in a loam soil at Sabour. With the further increase in the rate

of rice-husk application from 2.5 through 5.0, 7.5 to 10.0 Mg ha<sup>-1</sup> there was marginal increase in OC; the values of OC in plots treated with 5.0, 7.5 and 10.1 Mg ha<sup>-1</sup>, rice husk were 0.44, 0.45 and 0.43 per cent, respectively.

Sharma *et al.* (1988) reported a significant increase (by about 19 per cent) in OC from 1.12 to 1.33 per cent with the application of saw dust @ 7.5 Mg ha<sup>-1</sup> in a silty clay loam soil at Palampur (H.P.).

Biswas *et al.* (1970) reported increase in OC of a sandy loam soil by about 30 per cent over control with the use of ground nut cake @ equivalent to 45 kg N ha<sup>-1</sup> over a period of 10 years at Bhubneshwar (Orissa). The OC value increased from 0.37 per cent in control to 0.48 per cent with the treatment. Gupta *et al.* (1977) reported that application of sewage sludge @ 0, 112, 225 and 450 Mg ha<sup>-1</sup> to a sandy soil also increased the OM from 1 to 5 per cent. Sharma *et al.* (1988) reported an increase in OC by about 30 per cent over control when green *Lantana camara* was applied @ 7.5 Mg ha<sup>-1</sup> to a silty clay loam soil at Palampur; the OC content in control soil was 1.12 per cent. Similarly, Sharma *et al.* (1995) studied the effect of use of fresh lantana biomass @ 10, 20 and 30 Mg ha<sup>-1</sup> in a silty clay loam soil at Palampur (H.P) over a period of 6 years. They reported an increase in OC from 1.10 per cent in control to 1.23, 1.30 and 1.37 per cent with the three rates of lantana, respectively.

To summarise, the OC content of soils increased by 12-33 per cent over control with the use of different organic materials applied @ 10-75 Mg ha<sup>-1</sup> over a period of 2-12 years. FYM has been the most commonly used organic material. The effects of green manures have not been well documented. From these data, it is difficult to draw specific conclusions because

of large variability in the organic sources, soils, climatic conditions and method of handling of organic materials.

## 2.3 Effect of Organic Residues on Soil Physical Properties

### 2.3.1 Soil Structural Properties

a) **Soil Aggregation** : Effect of different types of organic materials, viz. FYM, poultry manure, pig dung, green manures, crop residues, rice husk, waste organic materials, industrial wastes etc. on aggregation have been studied in soils under rice-based cropping system. Of these, the most commonly used materials are FYM and green manures.

Kumar and Tripathi (1990) observed increase in mean weight diameter (MWD) and water-stable aggregates (WSA)  $> 0.25$  mm dia in a silty clay soil at Pantnagar (U.P.) with the addition of FYM @  $15 \text{ Mg ha}^{-1}$ . The MWD increased from 1.09 to 1.20 mm, and WSA  $> 0.25$  mm from 32.7 to 45.0 per cent. Bhagat and Verma (1991) reported increase in MWD from 0.61 to 0.81 mm, and WSA  $> 0.25$  mm dia from 69.7 to 80.7 per cent with the application of FYM @  $5 \text{ Mg ha}^{-1}$  for 5 years in a silty clay loam soil at Palampur (H.P.). Prasad (1994) reported increase in macro aggregates ( $> 1.0$  mm dia) from 6.5 to 10.6 per cent and micro aggregates ( $< 1.0$  mm dia) from 13.2 to 22.2 per cent with the incorporation of  $10 \text{ Mg ha}^{-1}$  FYM in a calcareous soil. Gupta *et al.* (1995) studied the effect of FYM @  $10 \text{ Mg ha}^{-1}$ , in combination with prilled urea (PU) and urea super granules (USG) @  $87 \text{ kg N ha}^{-1}$ , on soil aggregation in a clay soil at Sabour. The WSA  $> 0.25$  mm dia increased from 39.1 per cent in control to 56.9 per cent with 'FYM + PU', and 57.9 per cent with 'FYM + USG'.

Li and Zeng (1991) improved aggregation in a paddy soil in China by using pig dung @ 7.5-22.4 Mg ha<sup>-1</sup>. Sen *et al.* (1994) in a long-term experiment reported increase in micro aggregates (< 1.0 mm dia) in a paddy soil with the use of pig manure. Rixon *et al.* (1991), however, did not find significant change in aggregation with the use of pig dung @ 22.5 Mg ha<sup>-1</sup> for 3 years in a paddy soil in China.

Ram and Zwerman (1960) reported that aggregate stability is positively correlated with the quality and quantity of OM added to the soil. The effects and effectiveness vary with soil texture and green manure used, the effects last long if green manures are added continuously to the soil. MacRae and Mehuys (1985) reviewed the effect of green manures on aggregate distribution and stability in temperate areas. They reported that silt loam soils seem to be most responsive to aggregate-stability increases with green manuring; effects are more variable in clayey and sandy soils.

Darra *et al.* (1968) reported increase in WSA >0.25 mm dia from 6.74 per cent in control to 8.94 per cent with dhaincha (*Sesbania aculeata*) and 9.08 per cent with sanhemp (*Crotalaria juncea*) green manure in a clay loam soil at Kota (Rajasthan). Biswas *et al.* (1970) reported increase in WSA > 0.25 mm dia from 16.9 per cent in control to 28.2 per cent in a sandy loam soil treated with green manure @ equivalent to 45 kg N ha<sup>-1</sup> for a period of 10 years at Bhubneshwar (Orissa). Boparia *et al.* (1992) studied distribution of WSA in a sandy loam soil at Ludhiana (Punjab) treated with dhaincha (*Sesbania aculeata*) for 2 years. The WSA in the size range of 0.25-0.1 mm, 0.5-0.25 mm and >0.5 mm dia increased from 12.8 to 17.3 per cent, 9.4 to 10.5 per cent, and 3.9 to 4.6 per cent, respectively.

Mandal *et al.* (1992) reported increase in WSA ( 0.1-1.0 mm dia ) from 28.2 per cent in control to 32.5 and 33.3 per cent in a sandy clay loam soil treated with azolla @ 10 and 20 Mg ha<sup>-1</sup>, respectively for 2 years at Kalayani (West Bengal). Prasad (1994) reported increase in macro aggregates (> 1 mm dia ) in a calcareous soil from 5.6 to 9.6 per cent when treated with blue green algae @ 15 kg algal mass ha<sup>-1</sup>. The corresponding increase in micro aggregates (0.3 to 1.0 mm dia ) was from 13.2 to 20.0 per cent. They further reported that incorporation of 10 Mg ha<sup>-1</sup> FYM along with blue green algae further improved soil aggregation, although the effect was not substantial.

Yao (1984) observed significant increase in MWD ( from 0.16 to 3.71 mm ) when a paddy soil was treated with 'rice straw + milk vetch' (1:1 ratio) @ 20 Mg ha<sup>-1</sup> for 3 years in China. Bhagat and Verma (1991) reported increase in MWD from 0.61 mm to 0.74 mm in a silty clay loam soil at Palampur (H.P.) when supplied with rice straw @ 5 Mg ha<sup>-1</sup> for 5 years; the WSA > 0.25 mm dia increased from 69.7 to 77.3 per cent. They further stated that incorporation of FYM @ 5 Mg ha<sup>-1</sup> along with wheat straw further increased MWD to 0.83, mm and WSA > 0.25 mm dia to 81.2 per cent. Gupta *et al.* (1994) reported from Jabalpur increase in value of WSA >0.25 mm dia from 30.1 per cent in control to 62.0 and 64.8 per cent, respectively when rice soil was treated with rice straw @ 10 Mg ha<sup>-1</sup>, in combination with prilled urea (PU) and urea super granules (USG) @ 87 kg N ha<sup>-1</sup> each. According to these workers WSA of size range 0.1-0.25 mm dia decreased from 19.5 in control to 9.8 and 12.4 per cent with 'rice straw + PU' and 'rice straw + USG'.

Singh *et al.* (1976) reported increase in geometric mean diameter (GMD) from 0.413 to 0.493 mm with rice husk, and from 0.413 to 0.491 mm with wheat *bhusha* in a sandy loam soil

at Kharagpur (West Bengal); rice husk, and wheat *bhusha*, both, were applied @ 25 Mg ha<sup>-1</sup> for 2 years. The WSA > 0.25 mm dia were increased from 28.0 to 44.4 and 41.9 per cent with two materials. Gupta *et al.* (1994) reported that, at Sabour, incorporation of rice husk @ 10 Mg ha<sup>-1</sup> in a loam soil increased WSA > 0.25 mm dia from 23.6 to 48.2 per cent, while decreased WSA of size range 0.1-0.25 mm dia from 10.5 to 7.6 per cent.

Biswas *et al.* (1970) used groundnut cake to improve structure of rice soils. They reported increase in WSA > 0.25 mm dia from 29.5 to 35.1 per cent with groundnut cake @ equivalent to 45 kg N ha<sup>-1</sup> used for 10 years at Bhubneshwar (Orissa).

In a field study at Palampur Sharma *et al.* (1995) reported that 6 annual additions of fresh lantana biomass @ 30 Mg ha<sup>-1</sup> increased WSA > 0.25 mm dia from 2.66 to 4.09 mm in a silty clay loam soil.

To conclude, the MWD increased by 10-33 per cent with FYM, 19-2219 per cent with crop residues, and 13-54 per cent with other organic materials; WSA > 0.25 mm dia increased by 8-107 per cent with FYM, 7-204 per cent with green manure, 11-105 per cent with crop residues, and 8-18 per cent with other organic materials, applied @ 3-30 Mg ha<sup>-1</sup> over 2-12 years.

**b) Bulk density :** The addition of OM to a soil zone is expected to decrease the bulk density of that zone, because the added material is generally of low density than of soil matrix; the type of material used to affect such a change is largely inconsequent. However, the rate of application and the time allowed for the decomposition process to take place have significant effect on the bulk density values. Because of saturated water regime, the decomposition rate in

rice soils are quite different than those in arable soils, and hence the change in bulk density values due to the incorporation of organic residues will be different.

Low and Piper (1973) reported about 3 per cent decrease in bulk density of a loam soil, from 1.38 to 1.34  $\text{Mg m}^{-3}$ , with the application of 75  $\text{Mg ha}^{-1}$  FYM for 6 years. Bhadoria (1987) studied changes in bulk density of a sandy loam soil at Kharagpur (West Bengal) due to the application of FYM @ 25  $\text{Mg ha}^{-1}$  at two soil depths, i.e. 5 and 20 cm. Bulk density decreased from 1.85 to 1.73 (6.3 per cent decline), and 1.81 to 1.68  $\text{Mg m}^{-3}$  (7.2 per cent decline) at two depths, respectively. According to Sharma *et al.* (1987), application of FYM @ equivalent to 100  $\text{kg N ha}^{-1}$  to either rice or wheat or both the crops in a clay loam soil at Palampur (H.P.) for 6 years decreased the bulk density by 3.9, 3.9 and 7.8 per cent, respectively, over the control value of 1.28  $\text{Mg m}^{-3}$ . Similarly, in another experiment at Malan (H.P.), Ganai and Singh (1988) reported that incorporation of FYM @ 20  $\text{Mg ha}^{-1}$  for 2 years to rice or wheat decreased bulk density by 19.8 and 21.4 per cent over control value of 1.73  $\text{Mg m}^{-3}$ . Bhagat and Verma (1991) reported that bulk density of a silty clay loam soil at Palampur (H.P.) decreased from 1.32 to 1.26  $\text{Mg m}^{-3}$  (4.5 per cent decline) when the soil was treated with FYM @ 5  $\text{Mg ha}^{-1}$  for a period of 5 years. Patel *et al.* (1993) reported reduction in bulk density of a clayey soil at Navsari (Gujrat) from 1.41 to 1.36  $\text{Mg m}^{-3}$  (3.1 per cent decline) with the use of FYM @ 25  $\text{Mg ha}^{-1}$ . Studies conducted at different locations under an All India Co-ordinated Research Project also reported decrease in bulk density by 4 to 6 per cent in rice soils with the incorporation of FYM @ 5-10  $\text{Mg ha}^{-1} \text{ year}^{-1}$  over a period of time. Bulk density decreased from 1.21 to 1.16  $\text{Mg m}^{-3}$  in a clay soil at Jabalpur; from 1.50 to 1.53  $\text{Mg m}^{-3}$  in a

clay loam soil at Kaul (Haryana); from 1.23 to 1.16 Mg m<sup>-3</sup> in a black soil at Jabalpur; and from 1.54 to 1.45 Mg m<sup>-3</sup> at Sabour (Gupta *et al.*, 1994, 1995).

According to Darra *et al.* (1968) incorporation of dhaincha (*Sesbania aculeata*) and sanhamp (*Crotalaria juncea*) to rice during *kharif* did not show any effect on the bulk density of a clay loam soil observed after wheat harvest at Kota (Rajasthan). Incorporation of 7.5 Mg ha<sup>-1</sup> azolla or 22.5 Mg ha<sup>-1</sup> water hyacinth in a paddy soil for 2 years, decreased the bulk density from 1.23 to 1.11 Mg m<sup>-3</sup> (9.8 per cent decline) in China Yao, (1984). Boparai *et al.* (1992) also reported decrease in bulk density of a loamy sand soil at Ludhiana (Punjab) with the incorporation of 60 d-old dhaincha (*Sesbania aculeata*) green manure before rice for 2 years. In the first year of dhaincha incorporation the decrease in bulk density was from 1.61 to 1.57 Mg m<sup>-3</sup> (2.5 per cent decline) and 1.66 to 1.62 Mg m<sup>-3</sup> (2.4 per cent decline) at 0-15 and 15-30 cm depths. After two years the decrease in bulk density was from 1.58 to 1.38 Mg m<sup>-3</sup> (3.2 per cent decline) and from 1.66 to 1.61 Mg m<sup>-3</sup> (3.0 per cent decline) at two depths. Mandal *et al.* (1992) reported decrease in bulk density of a sandy clay loam soil at Kalayani (West Bengal) by 1.8 and 6.7 per cent over control (1.65 Mg m<sup>-3</sup>) with 10 and 20 Mg ha<sup>-1</sup> azolla after one year, and by 8.5 and 13.3 per cent after the second year. Thakur *et al.* (1995) observed significant decrease in bulk density of a silty clay loam soil at Palampur (H.P.) due to incorporation of dhaincha (*Sesbania aculeata*) and french bean biomass at an average rate of 18.3 and 1.3 Mg ha<sup>-1</sup> year<sup>-1</sup> after 3 years. The effect of dhaincha (*Sesbania aculeata*) was significantly higher than french bean probably because of much higher biomass added in the first case. Gupta *et al.* (1995) reported that in a clay loam soil at Kaul (Haryana) incorporation of dhaincha (*Sesbania aculeata*) @ 33 Mg ha<sup>-1</sup> decreased bulk density by 8.1 per cent at 0-15 cm

and 2.3 per cent at 15-30 cm depths over the control. The bulk density values in control and treated plots were 1.60 and 1.74  $\text{Mg m}^{-3}$  at 0-15 cm, and 1.75 and 1.71  $\text{Mg m}^{-3}$  at 15-30 cm soil depth. According to these workers, bulk density decreased by 9.1 per cent, from 1.54 to 1.40  $\text{Mg m}^{-3}$ , with the use of 'dhaincha + prilled urea' in a puddled clay soil at Sabour. Aggarwal *et al.* (1997) reported decrease in the bulk density of a clay loam soil from 1.69 to 1.60  $\text{Mg m}^{-3}$  (5.5 per cent drop) in 0-5 cm soil layer with the incorporation of 30-d-old dhaincha (*Sesbania aculeata*) @ 30  $\text{Mg ha}^{-1}$  in direct-seeded rice. Bulk density remained unaffected at 15-30 cm layer.

Yao, (1984) reported 4 per cent decrease in bulk density, from 1.18 to 1.14  $\text{Mg m}^{-3}$ , with the use of rice straw @ 4.5  $\text{Mg ha}^{-1}$  for 2 years in China. Bhadoria (1987) reported 13.5 per cent decrease in bulk density, from 1.85 to 1.60  $\text{Mg m}^{-3}$ , with the incorporation of rice husk @ 25  $\text{Mg ha}^{-1}$  in a sandy loam soil. Bhagat and Verma (1991) reported that incorporation of rice straw @ 5  $\text{Mg ha}^{-1}$ , alone or in combination with FYM @ 5  $\text{Mg ha}^{-1}$ , for 5 years, decreased bulk density in silty clay loam soil at Palampur (H.P.) by 5.3 and 10.6 per cent, respectively, over control. The bulk density value in control and plots treated with straw and 'straw + FYM' were 1.32, 1.25 and 1.18  $\text{Mg m}^{-3}$ , respectively. No change in bulk density was observed by More (1994) with the use of 'wheat straw + pressmud' @ 30  $\text{Mg ha}^{-1}$  (1:2 ratio) in a soil containing 46 per cent clay over a period of 3 years at Parbhani (Maharashtra). According to Gupta *et al.* (1994) bulk density of a clay soil decreased by 5.8 per cent over control (from 1.21 to 1.14  $\text{Mg m}^{-3}$ ) in 0-15 cm soil layer with the use of rice husk @ 5  $\text{Mg ha}^{-1}$ . Reduction in bulk density in a black clay soil at Jabalpur was from 1.23 to 1.16  $\text{Mg m}^{-3}$  (5.7 per cent drop), 1.30 to 1.24 (4.6 per cent drop) and 1.47 to 1.38  $\text{Mg m}^{-3}$  (6.1 per cent drop) at 0-10, 10-20 and 20-

30 cm depths, respectively, in response to rice husk incorporation @ 5 Mg ha<sup>-1</sup> (Gupta *et al.* 1995). They also reported decrease in bulk density of 0-20 cm layer of a black clay soil at Jabalpur with the incorporation of rice husk and rice straw each @ 5 Mg ha<sup>-1</sup>; bulk density at 20-30 cm layer remained practically unchanged. The bulk density values were 1.40, 1.52 and 1.62 Mg m<sup>-3</sup> in control, 1.43, 1.46 and 1.60 with rice husk, and 1.44, 1.51 and 1.61 Mg m<sup>-3</sup> with rice straw in 0-10, 10-20 and 20-30 cm soil layers, respectively. In a puddled clay soil at Sabour, Gupta *et al.* (1995) reported decrease in bulk density by 2.7 per cent, from 1.50 to 1.46 Mg m<sup>-3</sup>, in 0-10 cm soil layer. Bulk density in a loam soil decreased from 1.51 to 1.44 Mg m<sup>-3</sup> and 1.57 to 1.49 Mg m<sup>-3</sup> in 0-15 and 15-30 cm soil layer, with the use of rice husk @ 10 Mg ha<sup>-1</sup>. The decrease was 4.6 and 5.1 per cent over control, respectively. Combination of either prilled urea or urea super granules, to supply 87 kg N ha<sup>-1</sup>, with paddy straw decreased the bulk density by 9.1 and 5.8 per cent, respectively, of a clay soil at Sabour. The value decreased from 1.54 in control to 1.40 and 1.45 Mg m<sup>-3</sup> with the two urea forms, respectively.

Sharma *et al.* (1988) reported decrease in bulk density of a silty clay loam soil at Palampur (H.P.) from 1.24 to 1.21 Mg m<sup>-3</sup> (2.4 per cent decline over control) with the use of lantana @ 7.5 Mg ha<sup>-1</sup> (incorporation between rows); saw dust did not change the bulk density. Lantana incorporation @ 30 Mg ha<sup>-1</sup> for 6 years, in another experiment at Palampur (H.P.) (Sharma *et al.*, 1995), decreased the bulk density of a silty clay loam soil from 1.42 to 1.31 (7.7 per cent drop) at 0-7.5 cm and 1.48 to 1.38 Mg m<sup>-3</sup> (6.8 per cent drop) at 7.5-15 cm depth. The bulk density of aggregates (2-8 mm) and clods (4-6 cm) in the same experiment, decreased from 1.54 to 1.48 Mg m<sup>-3</sup> (3.9 per cent decrease) and 1.49 to 1.40 Mg m<sup>-3</sup> (6.0 per cent decrease).

Gupta *et al.* (1994) reported that incorporation of saw dust @ 5 Mg ha<sup>-1</sup> year<sup>-1</sup> in a black clay soil at Jabalpur decreased the bulk density of 0-15, 15-30 and 30-45 cm layers by 6.6, 4.8 and 2.9 per cent over control.

Thus, the bulk density decreased by 0-21 per cent with FYM @ 5-25 Mg ha<sup>-1</sup>, 2-17 per cent with green manures @ 1.3-22.5 Mg ha<sup>-1</sup>, 0-18 per cent with crop residues @ 4.5-25 Mg ha<sup>-1</sup>, and 2-30 per cent with other organic materials when applied @ 10-30 Mg ha<sup>-1</sup>, over a period of 2-7 years.

c) **Porosity** : Effect of FYM on soil porosity under rice- wheat cropping have been studied by various workers. Low and Piper (1973) reported that addition of 75 t FYM ha<sup>-1</sup> year<sup>-1</sup> for 6 consecutive years increased the total porosity of loam soil by 3.6 per cent, from 46.9 per cent in control to 48.6 per cent. In a silty clay loam soil at Palampur (H.P.), total porosity increased by 8.9 per cent when FYM was applied @ 5 Mg ha<sup>-1</sup> over a period of 5 years (Bhagat and Verma, 1991); the increase was from 49.9 to 53.0 per cent . According to Patel *et al.* (1993), the use of FYM @ 25 Mg ha<sup>-1</sup> for 6 years in a clayey soil under rice-wheat-green gram cropping sequence at Navasari (Gujrat), increased the total porosity from 46.0 to 48.0 per cent (4.3 per cent increase).

Green manuring with dhaincha (*Sesbania aculeata*) and sanhemp (*Crotalaria juncea*) increased the total porosity from 43.9 to 45.8 and 45.7 per cent, respectively, in a clay loam soil at Kota (Rajasthan) (Darra *et al.*, 1968). The per cent increase the total porosity over control was 4.5 and 4.1 per cent for dhaincha and sanhemp. Yao, (1984) in China reported increase in total porosity from 53.5 to 58.0 per cent (8.4 per cent increase) with azolla @ 7.5 Mg ha<sup>-1</sup>, and from 52.8 to 54.9 per cent (4 per cent increase) with water hyacinth @ 22.5 Mg ha<sup>-1</sup>. Azolla

and water hyacinth incorporation for 3 years, in another study, increased the total porosity from 54.0 and 53.0 per cent in control to 58.0 and 55.0 per cent (Gu and Wen, 1981). These treatments, however, did not affect the non-capillary porosity of soil. Mandal *et al.* (1992) reported from Kalayani (West Bengal) that the application of azolla @ 10 and 20 Mg ha<sup>-1</sup> in a sandy clay loam soil for 2 years increased the total porosity from 32.7 to 37.1 and 39.1 per cent; the increase over control being 13.6 and 19.9 per cent.

Bhagat and Verma (1991) reported that wheat straw incorporation @ 5 Mg ha<sup>-1</sup> in a silty clay loam soil at Palampur (H.P.) for 5 years increased the total porosity by 5.1 per cent over control, i.e. from 49.4 to 51.4 per cent. They further reported that wheat straw in combination with FYM @ 5 Mg ha<sup>-1</sup> further increased the total porosity to 54.6 per cent. In a field experiment, Sharma *et al.* (1995) reported that 6 annual additions of fresh lantana biomass @ 30 Mg ha<sup>-1</sup>, not only increased total porosity of whole soil from 42.2 to 46.0 per cent, but also of soil aggregates (2-8 mm dia) from 38.2 to 40.6 per cent, i.e. 6.3 per cent increase over control.

Use of organic materials also affect air-filled porosity of soils. Low and Piper (1973) observed that FYM @ 15 Mg ha<sup>-1</sup> year<sup>-1</sup> for 6 years increased the air-filled porosity at field capacity of a loamy soil from 8.3 in control to 9.5 per cent. Zhu and Yao (1993) reported that soils treated with organic materials were loose and air-filled pores increased more rapidly than in the control soil. Green manuring for three years also increased the aeration status of a saline coastal soil from 36.5 to 45.9 per cent, i.e. by 25.7 per cent over control (Liu, 1988).

These data show that the addition of organic residues increased, both, total and air-filled porosity. The total porosity increased by 3-7 per cent with FYM @ 5-75 Mg ha<sup>-1</sup>, by 4-20 per

cent with green manures @ 7.5-22.5 Mg ha<sup>-1</sup>, from 5-11 per cent with crop residues @ 5-10 Mg ha<sup>-1</sup> from 6-26 per cent with other organic materials @ 10-30 Mg ha<sup>-1</sup> for 2- 6 years.

**d) Soil Penetration Resistance :** Organic materials modify soil penetration resistance (SPR) by changing, both, the bulk density and water holding capacity of soils. Ganai and Singh (1988) in a field experiment at Malan (H.P.) reported that the incorporation of FYM @ 20 Mg ha<sup>-1</sup> for 2 years decreased the SPR of rice soil. The SPR decreased from 3.66 to 3.50 kg cm<sup>-2</sup> after rice, and from 3.74 to 3.64 kg cm<sup>-2</sup> after wheat harvest. Gupta *et al.* (1994) reported that application of FYM @ 5 Mg ha<sup>-1</sup> in a clay soil at Jabalpur 10 d-before puddling decreased the SPR from 3.22 to 2.61 kg cm<sup>-2</sup> at 5 cm depth, from 4.50 to 3.70 at 10 cm depth and from 5.36 to 4.49 kg cm<sup>-2</sup> at 15 cm depth. The per cent decrease over control was 19.0, 19.0 and 14.5 per cent, respectively. In another experiment at Jabalpur (Gupta *et al.*, 1995), decrease in SPR (from 3.1 to 2.6 kg cm<sup>-2</sup>) was significant only in the top 5 cm depth; at 10 and 15 cm depths change in SPR was marginal.

Gu and Wen (1981) reported that incorporation of green manures, like azolla and common water hyacinth, for a period of 3 years decreased the SPR of a rice soil by 9.7 and 16.2 per cent over control. The SPR value in control, and azolla- and water hyacinth-treated plots were 31.9, 28.0 and 26.0 kg cm<sup>-2</sup>, respectively. Yao (1984) in Japan reported decrease in SPR in a paddy soil with the use of azolla @ 7.5 Mg ha<sup>-1</sup> and water hyacinth @ 22.5 Mg ha<sup>-1</sup> over a period of 3 years in a paddy soil in China. The decrease was from 31.4 to 27.9 kg cm<sup>-2</sup>, i.e. 11.1 per cent with azolla and from 30.7 to 26.0 kg cm<sup>-2</sup>, i.e. 15 per cent with water hyacinth over a period of three years.

Gu and Wen (1981) observed decrease in SPR from 32.0 to 26.0 kg cm<sup>-2</sup> (18.8 per cent decrease over control) with the application of rice straw for 3 years in a paddy soil in China. At Jabalpur, in a black clay soil, Gupta *et al.* (1995) reported that use of rice straw and rice husk @ 5 Mg ha<sup>-1</sup> each decreased SPR at 0-5 cm depth from 3.1 to 2.9 and 2.9 kg cm<sup>-2</sup>, respectively. At 5-10 and 10-15 cm depths the decrease was from 5.6 to 5.2 and 5.3 kg cm<sup>-2</sup> with rice straw, and from 7.7 to 5.8 and 6.3 kg cm<sup>-2</sup> with rice husk. Fagi and De Datta (1983), however, did not find any effect of crop residues of upland crops planted before rice SPR in a sandy clay loam soil at IRRI, Philippines.

Bhagat *et al.* (1994) reported reduction in SPR of a rice soil, silty clay loam in texture, with the incorporation of fresh lantana biomass in soil before puddling, over a period of 3 years at Palampur (H.P.). The SPR values at 2.5, 7.5, 12.5 and 17.5 cm depths were 0.47, 0.60, 0.65 and 0.64 MPa in control, and 0.26, 0.28, 0.40 and 0.45 MPa, respectively, in plots treated with lantana @ 30 Mg ha<sup>-1</sup>. Gupta *et al.* (1994) reported that saw dust @ 5 Mg ha<sup>-1</sup> decreased the SPR of a black clay soil at Jabalpur upto 15 cm depth; the SPR decreased from 3.22 kg cm<sup>-2</sup> to 2.78, 4.58 to 3.78 and 5.36 to 5.19 kg cm<sup>-2</sup> at 5, 10 and 15 cm depths, respectively. The per cent decrease in SPR over control was 14.0, 18.0 and 3.0 at three depths, respectively.

These data conclude that SPR decreases with the additions of organic materials in soils. The SPR decreased by 0-19 per cent with FYM @ 5-22 Mg ha<sup>-1</sup>, by 10-16 per cent with green manures @ 7.5-22.5 Mg ha<sup>-1</sup>, by 1-34 per cent with crop residues @ 5-10 Mg ha<sup>-1</sup>, and 3-57 per cent with other organic residues @ 5-30 Mg ha<sup>-1</sup> used over a period 1-6 years.

**e) Other Structural Properties :** Other soil physical parameters which can be used as an index of structural status of rice soils include change in apparent specific volume ( $\Delta$  ASV),

coefficient of linear extensibility (COLE) and surface cracking behaviour etc. Very few studies have been conducted to investigate the effects of organic materials on these soil properties, especially under rice-wheat cropping.

Fagi and De Datta (1983) reported that incorporation of soybean and maize residues increased the change in apparent specific volume ( $\Delta$  ASV) of a rice soil. Soybean residue @ 11 Mg ha<sup>-1</sup> increased  $\Delta$  ASV from 0.13 to 0.27 cm<sup>3</sup> g<sup>-1</sup>, whereas maize residue @ 14 Mg ha<sup>-1</sup> increased  $\Delta$  ASV from 0.13 to 0.31 cm<sup>3</sup> g<sup>-1</sup>, at IRRI, Philippines.

Kumar *et al.* (1984) observed increase in COLE of a sandy soil from 0.060 to 0.064 cm cm<sup>-1</sup> due to the incorporation of FYM @ 846 Mg ha<sup>-1</sup> at PAU, Ludhiana (Punjab).

In a field experiment at HPKV, Palampur (H.P.) (Sharma *et al.*, 1995), incorporation of lantana @ 30 Mg ha<sup>-1</sup> for 6 years in a silty clay loam soil decreased volume of soil under cracks from  $5.0 \times 10^{-4}$  m<sup>3</sup> m<sup>-2</sup> to  $1.2 \times 10^{-4}$  m<sup>3</sup> m<sup>-2</sup> (76 per cent reduction). The cracking pattern changed from almost hexagonal deep cracks in control to close network of fine cracks in lantana treated soil.

### 2.3.2 Soil Hydrological Properties

a) **Water Retention and Availability :** Incorporation of organic materials invariably changes water retention as well as plant-available water capacity (PAWC) of soils. However, the magnitude of changes depends on whether the data are expressed on mass-basis or volume-basis. The expression of data on volume-basis are more meaningful, although the effects are less conspicuous in that case. The data in this review are presented on volume-basis or otherwise mentioned in the text.

Rixon *et al.* (1991) reported that with the addition of 22.5 Mg ha<sup>-1</sup> of pig dung in a barley-early rice-late rice cropping sequence, grown on a soil having 23 per cent clay in China, the water retention at 0.33 bar increased from 39.5 to 42.0 per cent, expressed on mass-basis.

Liu (1988) reported increase in maximum water holding capacity (WHC) from 43.6 to 46.5 mm, with the use of *Sesbania* green manure in a saline coastal soil. Mandal *et al.* (1992) reported that in sandy clay loam soil at Kalayani (West Bengal), use of 20 Mg ha<sup>-1</sup> azolla for 2 years increased the WHC from 31.5 to 38.0 per cent (mass-basis) in treated plots.

Kumar and Tripathi (1990) after 9 years of experimentation found that application of FYM @ 15 Mg ha<sup>-1</sup> year<sup>-1</sup> increased the moisture content at 0.33 bar from 30 to 32 per cent; water retention at higher suction remained unchanged. Thus, the PAWC increased from 17.0 to 20.0 per cent. Bhagat and Verma (1991) reported that application of FYM alone or in combination with rice straw, each @ 5 Mg ha<sup>-1</sup>, for 5 years in a silty clay loam soil at Palampur (H.P.) increased the water retention from 41.0 to 48.5 per cent at 0.33 bar, and 14.5 to 19.5 per cent at 15 bar suction. The PAWC increased from 26.5 per cent in control to 29.0 per cent in treated plots. Gupta *et al.* (1995) reported that incorporation of FYM @ 10 Mg ha<sup>-1</sup> in a black clay loam puddled soil at Kaul (Haryana) increased the water retention from 38.4 to 39.9 per cent at 0.33 suction, and from 22.4 to 22.8 per cent at 15 bar suction in 0-15 cm soil layer. Water retention was also improved at 15-30 cm depth; increase being from 38.9 to 47.3 per cent at 0.33 bar, and 24.3 to 25.3 per cent at 15 bar suction. The PAWC at two depths was increased from 16.0 and 14.6 per cent in control to 17.1 and 22.0 per cent, respectively.

Biswas *et al.* (1970) observed that in a sandy loam soil at Bhubneshwar (Orissa) use of green manures @ equivalent to 45 kg N ha<sup>-1</sup> for 10 years increased the water retention, both, at

0.33 and 15 bar suctions. The water retention increased from 13.4 to 17.2 per cent at 0.33 bar, and from 4.0 to 4.5 per cent at 15 bar suction. This led to a marginal increase in PAWC from 9.4 to 10.0 per cent on mass-basis.

Gupta *et al.* (1995) reported that mixing of combine-harvested wheat residues in a black clay loam soil at Kaul (Harayana) increased the water retention of 0-15 cm soil layer at 0.33 bar suction from 38.4 to 39.3 per cent, but did not affect water retention at 15 bar suction; the values at control and treated plots were 22.4 and 22.3 per cent. Thus, PAWC increased from 16.0 to 16.9 per cent. The corresponding increases in 15-30 cm soil layer was from 39.8 to 42.4 per cent at 0.33 bar, and 24.3 to 25.5 per cent at 15 bar; thereby increasing PAWC from 15.5 to 16.9 per cent.

Bhagat and Verma (1991) reported increase in the water retention from 41.0 to 44.0 per cent at 0.33 bar, and 14.5 to 17.5 per cent at 15 bar suction with the incorporation of rice straw @ 5 Mg ha<sup>-1</sup> for 5 years in a silty clay loam soil at Palampur (H.P.). The PAWC increased from 29.0 per cent to 35.0 per cent.

Singh *et al.* (1976) reported that the addition of wheat *bhusha* @ 25 Mg ha<sup>-1</sup> for 3 years increased the water retention of a sandy loam soil at Kharagpur (West Bengal). The water retention increased from 13.2 to 13.6 per cent at 0.33 bar and 4.9 to 5.2 per cent at 15 bar and the PAWC from 8.3 to 8.4 per cent, when expressed on mass-basis.

According to Bhagat *et al.* (1994), incorporation of fresh lantana @ 30 Mg ha<sup>-1</sup> in a silty clay loam soil at Palampur (H.P.) for 3 years increased the water retention from 40.0 to 48.0 per cent at 0.33 bar and from 11.0 to 13.0 per cent at 15 bar suction. The PAWC increased from 29.0 to 35.0 per cent.

According to Singh *et al.* (1976), incorporation of saw dust @ 25 Mg ha<sup>-1</sup> for 2 years increased the soil-water retention, both, at 0.33 and 15 bar suctions. The increase was from 13.3 to 14.3 per cent, and from 5.0 to 6.0 per cent at 0.33 and 15 bar suctions, respectively, on mass-basis. The PAWC thus, remained unchanged with saw dust treatment.

Biswas *et al.* (1970) and Singh *et al.* (1976), on the other hand, observed decline in PAWC, when expressed on mass-basis with the use of different organic materials due to more increase in water retention at 15 than at 0.33 bar suction. Use of neem cake @ equivalent to 45 kg N ha<sup>-1</sup> for 10 years in a sandy loam soil at Bhubneshwar (Orissa) decreased the water retention at 0.33 bar from 13.9 to 13.2 per cent, but increased water retention at 15 bar from 3.9 to 4.3 per cent (Biswas *et al.*, 1970). Thus, the PAWC decreased from 10.1 to 8.9 per cent, expressed on mass-basis. They also reported that use of FYM @ equivalent to 45 kg N ha<sup>-1</sup> for 10 years in a sandy loam soil at Bhubneshwar (Orissa) increased the water retention at 0.33 and 15 bar suctions from 13.9 to 14.3, and 3.9 to 4.4 per cent, respectively; the PAWC decreased from 10.1 to 9.6 per cent. Singh *et al.* (1976) observed appreciable decrease in water retention of a sandy loam soil at Kharagpur (West Bengal), when amended with FYM @ 25 Mg ha<sup>-1</sup>. Water retention increased from 13.3 to 13.6 per cent at 0.33 bar, and from 5.0 to 5.8 per cent at 15 bar suction, respectively. The available water decreased from 8.2 to 7.6 per cent, although the decrease was not statistically significant. They again reported that addition of rice husk @ 25 Mg ha<sup>-1</sup> for 2 years increased the water retention in a sandy loam soil at Kharagpur (West Bengal) at 15 bar (from 4.9 to 5.3 per cent), but not at 0.33 and suction (13.3 per cent). Thus, the PAWC decreased from 8.4 to 8.0 per cent with rice husk.

Gupta *et al.* (1995) also reported decrease in PAWC with the use of dhaincha @ 33 Mg ha<sup>-1</sup> in a puddled clay loam soil at Kaul (Haryana). The water retention at 0.33 bar decreased from 38.2 to 38.4 per cent and at 15 bar suction from 22.4 to 20.9 per cent; the PAWC decreased from 16.0 in control to 14.6 per cent in treated plots.

**b) Infiltration :** Sharma *et al.* (1987) observed an increase in the cumulative infiltration (over a period of 2 h) in a silty clay loam soil from 7.3 to 13.5 cm at Palampur (H.P.) with the continuous application of FYM @ equivalent to 100 kg N ha<sup>-1</sup> for 6 years to wheat in rice-wheat cropping sequence; when FYM was applied to rice, the cumulative infiltration increased to 11.7 cm; when FYM was applied to, both, rice and wheat crops, cumulative infiltration increased to 19.8 cm. Similar results were obtained by Ganai and Singh (1988). They reported that application of FYM @ 20 Mg ha<sup>-1</sup> for 2 years to wheat, increased the cumulative infiltration from 5.1 to 7.6 cm in 3 h period; when applied to rice, the value increase from 5.7 to 7.2 cm. According to Kumar and Tripathi (1990), final infiltrability of a silty clay loam soil treated with FYM @ 15 Mg ha<sup>-1</sup> for 9 years was 0.36 cm h<sup>-1</sup> as compared to 0.20 cm h<sup>-1</sup> in untreated control at wheat harvest at Pantnagar (U.P.). Bhagat and Verma (1991) reported that incorporation of FYM @ 5 Mg ha<sup>-1</sup> year<sup>-1</sup> in a silty clay loam soil at Palampur (H.P.) over a period of 5 years, increased the cumulative infiltration (observed for 15 h) from 0.48 to 0.56 m. More (1994) reported that incorporation of FYM @ 50 Mg ha<sup>-1</sup> for 3 years in a soil containing 46 per cent clay at Parbhani (Maharashtra) increased the infiltration rate from  $1.4 \times 10^{-6}$  to  $3.3 \times 10^{-6}$  m s<sup>-1</sup>; with biogas slurry @ 10 Mg ha<sup>-1</sup> the infiltration rate increased to  $1.4 \times 10^{-6}$  m s<sup>-1</sup>. Gupta *et al.* (1995) reported that incorporation of FYM @ 5 Mg ha<sup>-1</sup> increased the infiltration

rate in black clay soil at Jabalpur from 0.50 to 0.89 cm h<sup>-1</sup>. The cumulative infiltration increased from 6.8 to 15.6 cm after 6 hours.

Green manuring with dhaincha (*Sesbania aculeata*) increased water permeability in a clay loam soil at Kota (Rajasthan) from 0.027 to 0.091 cm h<sup>-1</sup> (Darra *et al.*, 1968); increased cumulative infiltration by 59 mm (in 300 min) over control when used for 3 years in a loamy sand soil at PAU, Ludhiana (Punjab) (Boparai *et al.*, 1992); decreased percolation rate in a sandy loam soil at PAU, Ludhiana from 12.1 to 11.6 mm d<sup>-1</sup>, when used for 6 years (Aggarwal *et al.*, 1995); and increased percolation rate in a clay loam soil from  $0.33 \times 10^{-6}$  to  $0.56 \times 10^{-6}$  m s<sup>-1</sup> when used for 2 years @ 13 Mg ha<sup>-1</sup> (Aggarwal *et al.*, 1997). Similarly, green manuring with sanhemp (*Crotalaria juncea*) increased water permeability from 0.027 to 0.044 cm h<sup>-1</sup> in a clay loam soil at Kota (Rajasthan) (Darra *et al.*, 1968); increased cumulative infiltration in a silty clay loam soil at Palampur (H.P.) when used for 3 years @ 18.3 Mg ha<sup>-1</sup> (Thakur *et al.*, 1995).

Burial of crop residues for 6 years increased the cumulative infiltration for 2 h of a clay loam soil at Palampur (H.P.) from 11.4 to 14.8 cm (Sharma *et al.*, 1987). Bhagat and Verma (1991) reported that application of rice straw @ 5 Mg ha<sup>-1</sup> for 5 years in silty clay loam soil at Palampur (H.P.) increased the cumulative infiltration observed for 15 hours from 0.48 m in control to 0.53 m. Combined application of wheat straw @ 10 Mg ha<sup>-1</sup> and pressmud @ 20 Mg ha<sup>-1</sup> to a soil having 46 per cent clay at Parbhani (Maharashtra) for 3 years increased the infiltration rate from  $1.9 \times 10^{-6}$  to  $2.8 \times 10^{-6}$  m s<sup>-1</sup> (More, 1994). According to Gupta *et al.* (1995), use of rice husk @ 5 Mg ha<sup>-1</sup> in a black soil at Jabalpur increased the infiltration rate

from 0.50 to 0.85 cm h<sup>-1</sup>; infiltration rate was doubled with rice straw @ 5 Mg ha<sup>-1</sup> from 0.50 to 1.00 cm h<sup>-1</sup>.

Use of fresh lantana biomass @ 30 Mg ha<sup>-1</sup> for 3 years increased the infiltration rate in a silty clay loam soil at Palampur (H.P.) from 0.09 to 0.27 cm h<sup>-1</sup> (Bhagat *et al.*, 1994). More (1994) reported increase in infiltration rate from  $1.4 \times 10^{-6}$  to  $2.8 \times 10^{-6}$  m s<sup>-1</sup> with the pressmud @ 20 Mg ha<sup>-1</sup> used for 3 years in a soil having 46 per cent clay at Parbhani (Maharashtra).

The infiltration rate, cumulative infiltration and percolation rate were increased with the addition of different types of organic materials. The increase in infiltration rate was 78-136 per cent with FYM, 8.7-100 per cent with crop residues, and 100-200 per cent with other materials; in cumulative infiltration from 17-129 per cent with FYM and 10-30 per cent with crop residues; and in percolation rate from 63-237 per cent with green manures, when used @ 2-35 Mg ha<sup>-1</sup> over a period of 2-9 years.

**c) Hydraulic Conductivity :** Applications of FYM over a period of time have generally been seen to increase the saturated hydraulic conductivity (Ks) of soils under rice-wheat cropping. Bhagat and Verma (1991) observed about 4 times increase in Ks from  $0.80 \times 10^{-6}$  to  $3.21 \times 10^{-6}$  m s<sup>-1</sup> in a silty clay loam soil at Palampur (H.P.) with FYM @ 5 Mg ha<sup>-1</sup> used for 5 years. Gupta *et al.* (1995) reported 2.5 times increase in Ks from 0.26 to 0.64 cm h<sup>-1</sup> in a black clay soil at Jabalpur with FYM @ 5 Mg ha<sup>-1</sup>. Prasad (1994) reported that use of FYM @ 10 Mg ha<sup>-1</sup> increased Ks of a soil from 0.221 to 0.368 cm h<sup>-1</sup>. Gupta *et al.* (1995) reported about 8-fold increase in Ks from 0.15 to 1.24 cm h<sup>-1</sup> in a puddled clay loam soil at Kaul (Haryana) with FYM @ 20 Mg ha<sup>-1</sup>. Aggarwal *et al.* (1995) reported that in a Fatehpur sandy loam soil at Ludhiana

(Punjab) use of FYM @ 20 Mg ha<sup>-1</sup> for 6 years increased the average percolation rate from 12.2 mm d<sup>-1</sup> to 13.1 mm d<sup>-1</sup>.

Biswas *et al.* (1970) did not find any change in Ks of a sandy loam soil at Bhubneshwar (Orissa) with use of FYM @ equivalent to 45 kg N ha<sup>-1</sup> for 10 years, but with green manuring, at the same rate, from 0.25 to 0.30 cm h<sup>-1</sup>. Joshi *et al.* (1994) observed increase in Ks of a clay loam soil from 3.1 to 4.8 cm d<sup>-1</sup> when green manured with dhaincha (*Sesbania aculeata*). According to these workers, dhaincha (*Sesbania aculeata*) was superior to the incorporation of *Leucaena leucocephala* leaves or weeds in rice-wheat sequence. Prasad (1994) reported that use of blue green algae @ 15 kg ha<sup>-1</sup> algal crust, alone or in combination with FYM @ 10 Mg ha<sup>-1</sup>, increased Ks from 0.221 to 0.254 and 0.441 cm h<sup>-1</sup>, respectively. At Kaul (Haryana), use of dhaincha @ 33 Mg ha<sup>-1</sup> as green manure caused about 3-fold increase in Ks (from 0.055 to 0.160 cm h<sup>-1</sup>) in a puddled clay loam soil (Gupta *et al.*, 1995). Aggarwal *et al.* (1997) reported that incorporation of 30-d-old dhaincha @ 13 Mg ha<sup>-1</sup> in clay loam soil nearly doubled Ks (from  $1.36 \times 10^{-6}$  to  $2.64 \times 10^{-6}$  m s<sup>-1</sup>); Ks was determined 30-d-after direct sowing of rice. The value of Ks increased from  $0.56 \times 10^{-6}$  in control to  $1.19 \times 10^{-6}$  m s<sup>-1</sup> after 2 years of continuous green manuring. Aggarwal *et al.* (1995) reported decrease in percolation rate of in a sandy loam soil from 12.2 to 11.6 mm d<sup>-1</sup> when manured with dhaincha (*Sesbania aculeata*) @ equivalent to 140 kg N ha<sup>-1</sup> for 6 years.

Bhagat and Verma (1991) reported about 4-fold increase in Ks (from  $0.80 \times 10^{-6}$  to  $3.21 \times 10^{-6}$  m s<sup>-1</sup>) with the incorporation of 'rice straw + FYM' each @ 5 Mg ha<sup>-1</sup> in a silty clay loam soil at Palampur (H.P.). Gupta *et al.* (1995) reported increase in Ks from 0.6 to 0.9 cm h<sup>-1</sup>

with rice straw @ 5 Mg ha<sup>-1</sup>, and from 0.221 to 0.485 cm h<sup>-1</sup> with rice straw @ 10 Mg ha<sup>-1</sup>, at two locations in Sabour. They further reported that in a field experiment at Sabour, use of rice straw @ 10 Mg ha<sup>-1</sup> along with prilled urea (PU) or urea super granules (USG) @ 87 kg N ha<sup>-1</sup>, increased the Ks of a puddled clay soil from 0.136 to 0.396 and 0.415 cm h<sup>-1</sup>, respectively.

Gupta *et al.* (1994, 1995) have reported the effect of rice husk @ 5 Mg ha<sup>-1</sup> on Ks at two locations. At Jabalpur, in a puddled clay soil, Ks increased from 0.28 to 0.51 cm h<sup>-1</sup>, and at Sabour, in a puddled loam soil, Ks increased from 0.6 to 0.8 cm h<sup>-1</sup>.

Effect of groundnut cake, compost and lantana etc. on Ks of rice soil have also been studied by some workers. Biswas *et al.* (1970) reported that groundnut cake @ equivalent to 45 kg N ha<sup>-1</sup> for 10 years in a sandy loam soil at Bhubneshwar (Orissa) increased Ks from 0.25 to 0.31 cm h<sup>-1</sup>. Shin and Shin (1975) observed increase in Ks of a rice soil in Japan from 2.96 to 5.21 cm h<sup>-1</sup> with the use of compost @ 7.5 Mg ha<sup>-1</sup> for 20 years. Bhagat *et al.* (1994) reported increase in Ks in a silty clay loam soil from  $3.88 \times 10^{-7}$  to  $8.33 \times 10^{-7}$  m s<sup>-1</sup> with the use of lantana @ 30 Mg ha<sup>-1</sup> over a period of 3 years.

According to these reports, with few exceptions, where no change in Ks was observed, the use of organic residues invariably increased Ks of soils. The Ks of rice soils increased by 7-727 per cent with FYM @ 5-20 Mg ha<sup>-1</sup>, 15-191 per cent with green manures @ 13-33 Mg ha<sup>-1</sup>, 30-301 per cent with crop residues @ 5-10 Mg ha<sup>-1</sup> and 24-115 per cent with other organic materials applied @ 7.5-30 Mg ha<sup>-1</sup>, over a period of 2-20 years.

**d) Soil-Water Contact Angle :** Very few reports are available on the effect of organic materials on soil-water contact angle. Das and Das (1972) determined soil-water contact angle in samples from two soil horizons, differing mainly in OC content. The contact angle was 79.1°

for surface horizon (0-18.5 cm) which had 6.84 per cent OC, and  $76.0^\circ$  for subsurface horizon (18.5-33.5 cm) which had 3.57 per cent OC. Thus increase in soil OC increased soil-water contact angle, making soil less hydrophilic. Similar observations were made by Kumar *et al* (1984) in a pot experiment; the contact angle of Ludas sand increased from  $33.3^\circ$  to  $51.2$ ,  $72.5$ ,  $85.1$  and  $85.9^\circ$ , when the sand was treated for 10 months with FYM @ 133, 270, 540 and  $846 \text{ Mg ha}^{-1}$ , respectively.

### 2.3.3 Mechanical Properties

a) **Soil Consistency Limits** : The soil consistency limits include properties like liquid limit, plastic limit, shrinkage limit and plasticity index. Very few studies have addressed to changes in soil consistency limits with the use of organic materials, especially in rice-based cropping system. Jo (1990) reported that application of compost @  $7.5 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  for 20 years increased the liquid limit of a rice soil from 32.2 to 34.5 per cent, plastic limit from 28.4 to 30.2 per cent and plasticity index from 3.8 to 4.2 per cent. In a soil under barley-early rice-late rice rotation, Rixon *et al.* (1991) observed that application of pig dung @  $22.5 \text{ Mg ha}^{-1}$  before rice crop increased the liquid limit from 41.0 to 42.0 per cent, plastic limit soil from 30.0 to 30.8 per cent and plasticity index from 11.0 to 11.2 per cent; when the material was applied to barley, the values were 43.1, 30.0 and 13.1 per cent, respectively; the values with the use of rice straw @  $22.5 \text{ Mg ha}^{-1}$  to late rice were 42.3, 29.6 and 12.7 per cent, respectively. The effects, if any, appeared marginal.

b) **Energy Required for Land Preparation** : Low and Piper (1973) reported that use of FYM @  $7.5 \text{ Mg ha}^{-1} \text{ year}^{-1}$  in a loam soil decreased the draw-bar pull (draft force recorded during ploughing at 15-cm depth using a single furrow plough) from 1.66 in control to 1.54 kN,

which is 8.4 per cent less as compared to control. Fagi and De Datta (1983) compared the effect of incorporation of soybean residue in puddled wet-land and non-puddled dry-land rice in a silty clay soil. They observed that the energy required to plough one hectare of land after rice harvest decreased by almost 15 per cent, from  $1.21 \times 10^9$  to  $1.03 \times 10^9$  J. Bhagat *et al.* (1994) reported that application of fresh lantana biomass @  $30 \text{ Mg ha}^{-1}$  for 3 years decreased the draft requirement by 36 per cent, from 5.35 to 3.24 GJ  $\text{ha}^{-1}$ , in a silty clay loam soil under rice-wheat cropping.

c) **Clod Breaking Strength :** Sharma *et al.* (1995) observed that fresh lantana biomass @ 10, 20 and  $30 \text{ Mg ha}^{-1}$  for 6 years in a silty clay loam soil decreased the clod breaking strength from 419.9 to 377.2, 220.8 and 215.6 kPa, respectively, which was about 10, 47, and 49 per cent lower as compared to control.

## 2.4 Effect of Organic Materials on Crop Yields in Rice-Wheat Sequence

Recycling of organic residues into soil has long been seen to increase soil productivity and crop yields. The benefits of organic residues have been attributed to improvement in chemical, physical and biological properties of soils. Increases in yields of individual crops due to organic manuring have amply been reported in literature. This para reviews literature on the effects of organic manuring on the productivity of rice-wheat cropping system as a whole. Use of different types of organic materials, like FYM, crop residues, green manures, pressmud, biogas slurry, saw dust, rice husk etc., either alone or in combinations, to improve productivity of rice-wheat cropping have been reported. The organic residues have mostly been incorporated into soils before transplanting of rice.

Maskina *et al.* (1988) used FYM @ 12 Mg ha<sup>-1</sup> year<sup>-1</sup> to improve the grain yield of rice and wheat in a loamy sand soil. Five years' pooled data indicate that the FYM, without any chemical fertiliser, increased the yield of wetland rice from 2.8 to 3.7 Mg ha<sup>-1</sup> (32 per cent increase). Grain yield of the following wheat crop increased from 1.3 to 3.9 Mg ha<sup>-1</sup> (200 per cent increase). Thus, the total 'rice + wheat' productivity increased by 85 per cent over the control. The treatment started showing effect in the first cropping season itself. Soni and Sikarwar (1991) also reported increase in the grain yields of rice and wheat with FYM @ 12 Mg ha<sup>-1</sup> at four locations. The rice yield increased from 1.78 to 2.15 Mg ha<sup>-1</sup> at Kalyani (West Bengal), from 1.35 to 1.54 Mg ha<sup>-1</sup> at Pusa farm (U.P.), from 0.92 to 1.32 Mg ha<sup>-1</sup> at Masoda (U.P.) and from 3.06 to 4.03 Mg ha<sup>-1</sup> at Karjat (Maharashtra). The increases in wheat yield, without the use of chemical fertilisers, were from 1.94 to 2.34, 1.24 to 1.57, 0.93 to 1.20 and from 0.36 to 0.86 Mg ha<sup>-1</sup>, at four locations, respectively. The FYM @ 12 Mg ha<sup>-1</sup> along with chemical fertilisers @ 60 kg N, 30 kg P<sub>2</sub>O<sub>5</sub> and 30 kg K<sub>2</sub>O ha<sup>-1</sup> to, both, rice and wheat, increased the rice yields from 2.95 to 3.26, 1.93 to 2.34, 3.21 to 3.32 and 4.60 to 5.08 Mg ha<sup>-1</sup>, and wheat yields from 2.84 to 3.44, 2.24 to 2.49, 3.09 to 3.39 and 1.21 to 1.34 Mg ha<sup>-1</sup>, at the four locations, respectively. Thus, the use of FYM increased total productivity of 'rice + wheat' by 20.7, 20.1, 36.2 and 42.1 per cent without chemical fertilisers, and 15.7, 15.8, 56.0 and 34.1 per cent with chemical fertilisers, respectively.

According to Bhandari *et al.* (1992), on the basis of 4-y field experimentation, it was not possible to substitute fertiliser N with FYM even to the tune of 25 per cent in a loamy sand soil. With 25 per cent substitution of fertiliser N with FYM, the grain yield decreased from 6.28 to 5.83 Mg ha<sup>-1</sup> in case of rice, and from 4.39 to 3.93 Mg ha<sup>-1</sup> in case of wheat. However,

green manuring with jantar (*Sesbania aculeata*), for compensating 50 per cent N, along with 50 per cent NPK through fertilisers to rice, produced as much rice yield ( $6.27 \text{ Mg ha}^{-1}$ ) as the 100 per cent recommended NPK through chemical fertilisers ( $6.28 \text{ Mg ha}^{-1}$ ). Inclusion of a short duration mung-bean crop before rice not only produced  $1.10 \text{ Mg ha}^{-1}$  grain yield (mung-bean), but also substituted 50 per cent NPK for rice. Wheat yields following rice with 100 per cent NPK were 4.39, 4.31 and  $4.21 \text{ Mg ha}^{-1}$  in control (without organic manuring), green manured and mung-bean straw-added plots, respectively.

More (1994) compared pressmud, dried biogas slurry, FYM and wheat straw, alone or in combinations, for their effect on the productivity of rice-wheat cropping system for 3 years in a sodic clay soil. The application of organic materials to soil enhanced significantly the grain and straw yields of wheat. The effectiveness of different treatments on crop yields was in the order: 'FYM ( $25 \text{ Mg ha}^{-1}$ ) + pressmud ( $20 \text{ Mg ha}^{-1}$ )' > FYM ( $50 \text{ Mg ha}^{-1}$ ) > dried biogas slurry ( $10 \text{ Mg ha}^{-1}$ ) > pressmud ( $20 \text{ Mg ha}^{-1}$ ) > 'wheat straw ( $10 \text{ Mg ha}^{-1}$ ) + FYM ( $25 \text{ Mg ha}^{-1}$ )' > 'wheat straw ( $10 \text{ Mg ha}^{-1}$ ) + pressmud ( $20 \text{ Mg ha}^{-1}$ )'. Based on the data pooled for 3 years, rice grain yield with 'FYM + pressmud' and FYM alone increased from  $0.80 \text{ Mg ha}^{-1}$  in control to 1.82 and  $1.65 \text{ Mg ha}^{-1}$ . The corresponding increases in the wheat yield were from 0.88 to 1.98 and  $1.78 \text{ Mg ha}^{-1}$ , respectively. Thus, the total productivity of 'rice + wheat' system increased by 126 and 104 per cent with 'FYM + pressmud' and FYM, respectively.

Prasad (1994), based on the data from some field experiments, concluded that 'compost @  $10 \text{ Mg ha}^{-1}$  + blue green algae (BGA) @  $15 \text{ kg ha}^{-1}$ ' was effective in improving the productivity of rice-wheat cropping system. He observed residual effect equivalent to 20 kg N, 12 kg  $\text{P}_2\text{O}_5$  and  $8 \text{ kg K}_2\text{O ha}^{-1}$  on the yield of succeeding wheat crop. He further concluded that

biogas slurry, FYM and water hyacinth compost @ 10 Mg ha<sup>-1</sup> each contributed 60 kg P<sub>2</sub>O<sub>5</sub> in rice-wheat cropping system. When supplemented with 100 per cent NPK, the rice yield increased from 3.22 Mg ha<sup>-1</sup> in control to 3.61 Mg ha<sup>-1</sup> with FYM @ 10 Mg ha<sup>-1</sup>, 3.21 with BGA @ 15 kg ha<sup>-1</sup>, and 3.49 with 'FYM + BGA'; the corresponding increases in wheat yields were from 3.64 to 4.09, 3.91 and 4.21 Mg ha<sup>-1</sup>, respectively. The total productivity of rice-wheat system increased by 11.3, 2.9 and 11.3 per cent over control (7.7 Mg ha<sup>-1</sup>) with FYM, BGA and 'FYM + BGA', respectively.

Aggarwal *et al.* (1995) did not observe any effect of FYM @ equivalent to 120 kg N ha<sup>-1</sup> (20 Mg ha<sup>-1</sup>) or green manuring @ equivalent to 140 kg N ha<sup>-1</sup> along with 60 kg N through urea on rice yield upto 6 years in a sandy loam soil compared to control (60 kg N ha<sup>-1</sup> through urea). However the wheat yield showed significant increase from second year onwards with 'urea + FYM' treatment.

Gupta *et al.* (1995) compiled data from different locations under AICRP and concluded that application of organic residues, like FYM, rice husk, saw dust and green manures before rice increased grain yield under rice-wheat cropping. FYM, in general, was found superior to other organic materials. Rice yields increased from 2.44-7.01 to 2.74-7.36 Mg ha<sup>-1</sup>, and wheat yields from 0.98-4.46 to 1.29-4.82 Mg ha<sup>-1</sup> with organic residue recycling. The over all increase in the productivity of rice-wheat cropping was from 3.93-11.68 to 4.36-12.23 Mg ha<sup>-1</sup>.

According to Kumar and Yadav (1995), in a long-term experiment established in a sodic silty loam soil, 25 -50 per cent substitution of N through organic source (FYM, green manuring with *Sesbania aculeata* and *Sesbania cannabina*, and wheat straw) reduced the rice yield by 6-23 per cent compared to 100 per cent NPK alone for first three years. In the following years,

25-50 per cent N through FYM or green manure along with 50-75 per cent NPK to rice gave equal or more rice yield compared to 100 per cent NPK. Wheat yields for the first three years remained unchanged with FYM or green manure treatments. After three years, the substitution of chemical fertilisers with organic manures increased wheat yield. Additions of wheat straw did not show any visible residual effect on wheat yield.

Mahapatra and Sharma (1995) could increase grain yield of 'rice + wheat' from 4.35 Mg ha<sup>-1</sup> in control to 8.40 Mg ha<sup>-1</sup> with dhaincha (*Sesbania aculeata*) green manure, and 9.10 Mg ha<sup>-1</sup> with 'dhaincha + 30 kg N ha<sup>-1</sup>'. The yield with 120 kg fertiliser N ha<sup>-1</sup> was 8.2 Mg ha<sup>-1</sup>.

Pathak and Sarkar (1995) compared the effects of dhaincha (*Sesbania aculeata*) green manure, FYM, biogas slurry and rice straw on the productivity of rice-wheat cropping. FYM, biogas slurry and green manure along with urea in 50:50 ratio on N equivalent basis produced almost the same grain yield of rice (3.91-4.36 Mg ha<sup>-1</sup>) and wheat (3.03-3.37 Mg ha<sup>-1</sup>) as urea alone (4.24 Mg ha<sup>-1</sup> rice grains and, 3.27 Mg ha<sup>-1</sup> wheat grains). Rice yield was lowest (3.52 Mg ha<sup>-1</sup>) with 'rice straw + urea', while wheat yield with this treatment was the same (3.81 Mg ha<sup>-1</sup>) as with other organic sources.

Tiwari *et al.* (1995) compared the effects of *Sesbania rostrata* and *Sesbania cannabina* along with different levels of fertiliser N on the productivity of rice and wheat in a silty clay loam soil. They observed that the productivity of the total system increased from 6.26 Mg ha<sup>-1</sup> without green manure to 7.77 and 7.67 Mg ha<sup>-1</sup> with *Sesbania rostrata* and *Sesbania cannabina*, respectively.

According to these data, soil incorporations of different organic materials before transplanting of rice increased the total productivity of 'rice+wheat' cropping on an average by

2.9 to 126.2 per cent over control. The increases in crop yields were attributed to improvement in soil physical properties, like bulk density, penetration resistance, aggregation, hydraulic conductivity, infiltration and moisture retention (Prasad, 1994; More, 1994; Gupta et al., 1995; Aggarwal et al., 1997; Mishra and Sharma 1997), and chemical properties, like organic carbon, available macro- and micro- nutrients like Zn, Cu, Mn and Fe etc. (Maskina et al., 1988; Bhandari et al., 1992; Prasad, 1994; Aggarwal et al., 1995; Kumar and Yadav, 1995; Mahapatra and Sharma, 1995; Pathak and Sarkar, 1995; Tiwari et al., 1995). Chemical changes increased the nutrient supplying power of rice soils. In case of sodic soils, organic mixing decreased pH, EC, and ESP thereby increasing crop yields (More, 1994; Kumar and Yadav, 1995).

## **2.5 Research Gaps :**

1) Several studies have reported increases in crop yields in rice-wheat sequence with organic manuring. The increases in crop yields have generally been associated with the improvement in soil chemical and physical properties. However, there is a general lack of quantitative data supporting relationship between crop yields and soil physical properties. There is a need to specifically work out changes in soil physical properties due to the use of different kinds of organic residues and relate them quantitatively with the crop yields under different agro-ecological situations.

2) Quantitative data are required to distinguish between the effects of chemical and physical properties of soils, modified due to recycling of organic residues in soils, on crop yields.

3) The farm yard manure, green manures and crop residues have by far been the major organic sources in amending rice soils. Most of these materials are in limited supply and have several alternate uses. There is a need to identify and test the organic waste materials which are locally available and have few alternate uses, such as fodder and fuel.

4) Criteria have not been developed for characterising physical conditions of soils in relation to plant growth, probably because of strong interdependence of different soil physical properties and their interactive effects on plant growth. However, in order to evaluate the effects of different treatments on the improvement of soil physical environment, it is important to develop a single value soil physical index.



**MATERIAL  
AND  
METHODS**

### **III MATERIAL AND METHODS**

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The present investigation was carried out in an ongoing long-term experiment established in *kharif* (wet season), 1987. The details of the field experiment and methodology adopted have been described under the following heads :

- 3.1 General Description of the Study Area
  - 3.1.1 Location
  - 3.1.2 Climate
  - 3.1.3 Soils
- 3.2 Experimental Background
- 3.3 Treatment Details
- 3.4 Soil Observations
  - 3.4.1 Organic Carbon
  - 3.4.2 Soil Physical Properties
    - 3.4.2.1 Soil Temperature
    - 3.4.2.2 Soil Colour
    - 3.4.2.3 Structural properties
    - 3.4.2.4 Hydraulic Properties
    - 3.4.2.5 Mechanical Properties
  - 3.4.3 Non-Limiting Water Range
- 3.5 Plant Observations
  - 3.5.1 Crop Yields
  - 3.5.2 Root Studies
    - 3.5.2.1 Spatial Distribution of Roots
    - 3.5.2.2 Root Mass Density and Shoot/Root Ratio
- 3.6 Distinguishing between effects of physical and chemical properties of soil on wheat crop
- 3.7 Statistical Analysis

### 3.1 General Description of the Study Area

#### 3.1.1 Location

The experiment was conducted at the experimental farm of the Department of Soil Science, HPKV, Palampur (H.P.). The experimental site is situated at 32° 6' N latitude and 76° 3' E longitude at an elevation of 1290 m above mean sea level. The area lies in the Palam Valley of Kangra District in the foot-hills of Dhauladhar range. It represents the high rainfall mid-hill wet-temperate zone of Himachal Pradesh in North-west Himalayas.

#### 3.1.2 Climate

The climate of the area is wet temperate characterized by severe winters and mild summers. Annual mean temperature varies from 8.2°C in January to around 28.0°C during the hottest month of June. The annual rainfall of the area ranges from 2500 to 3000 mm. The distribution of rainfall is uneven. About 80 per cent of it is received during mid June to mid September, the main *kharif* season. The mean relative humidity in the region varies from 46 to 84 per cent; the minimum being in May and maximum in July/August.

#### 3.1.3 Soils

Taxonomically, the experimental soil is classified under the order "Alfisol" and subgroup Typic Hapludalf (Verma, 1979). According to the Genetic System of Classification, the soils of the area are classified as Gray Brown Podzols. The soils have been developed from fluvioglacial parent material. These soils owe their origin to rocks, like slate, phyllites, quartzites, schists and gneisses. The soils are acidic in reaction (pH 5.2 to 6.2). Important physical, chemical and physio-chemical properties of the experimental soil are given in Table 1.

Table 1. Important physical, chemical and physico-chemical properties of experimental soil at the initiation of experiment.

Parameter	Value	Method used
<b>Mechanical Analysis :</b>		
1) Sand (%)	16.8	International Pipette Method
2) Silt (%)	52.7	(Piper, 1966)
3) Clay (%)	30.0	
Textural Class	Silty clay loam	International Society of Soil Science (ISSS) Textural diagram
pH (1:1.25, H <sub>2</sub> O)	5.8	Expanded Scale pH meter (Jackson, 1967)
Organic Carbon (g kg <sup>-1</sup> soil)	8.8	Rapid Titration Method (Walkley and Black, 1934)
Cation Exchange Capacity (c mol [p] <sup>+</sup> kg <sup>-1</sup> )	11.8	Neutral Normal Ammonium Acetate Method (Black, 1965)
Available N (mg kg <sup>-1</sup> soil)	120	Alkaline Permanganate Method (Subbiah and Asija, 1956)
Available P (mg kg <sup>-1</sup> soil)	8	0.5 M NaHCO <sub>3</sub> (pH 8.5) Method (Olsen <i>et al.</i> , 1954)
Available K (mg kg <sup>-1</sup> soil)	76	Neutral Normal Ammonium Acetate Method (Hanway and Heidal, 1952)

### 3.2 Experimental Background

The experiment was established during *kharif*, 1987 with four levels of lantana-boimass incorporation (0, 10, 20 and 30 Mg ha<sup>-1</sup> on fresh weight basis) and three methods of land preparation (no puddling, puddling and soil compaction), in three replications in randomized

complete block design for rice. The lantana was incorporated into the soil about 10-12 days before transplanting of rice seedlings. All the rice plots received nutrients at recommended rates (90N-18P-33K kg ha<sup>-1</sup>). Wheat followed rice as a general crop, receiving nutrients at recommended rates (120N-39P-25K kg ha<sup>-1</sup>). The experiment was modified in *kharif*, 1993, when three land preparation methods were replaced by three N application rates to rice, viz. 50, 75 and 100 per cent of recommended N. The P and K were applied at the recommended rates. Rice was transplanted in puddled soil. Wheat crop received 100, 75 and 50 per cent of recommended N in the plots receiving 50, 75 and 100 per cent N during rice crop, respectively. On the basis of results obtained, the fertilizer treatments were again modified in *kharif*, 1996. The N levels were replaced by three NPK levels, i.e. 50, 75 and 100 per cent of recommended NPK to rice. The following wheat crop received an uniform application of fertilizers @ 75 per cent of recommended NPK. Due to high incidence of blast during *kharif*, 1996 the fertilizer levels were again modified during *kharif*, 1997 to 33, 66 and 100 per cent of recommended NK to rice and an uniform dose of 66 per cent of recommended NPK to wheat. Due to substantial build-up of P in the soil, the P application to rice was omitted.

### 3.3 Treatment Details

The treatment details of the experiment during the period of study were :

#### A. Rice Crop

i) <u>Lantana Levels</u>	<u>1996-97</u>	<u>1997-98</u>
M <sub>0</sub>	no lantana	no lantana
M <sub>1</sub>	10 Mg ha <sup>-1</sup>	10 Mg ha <sup>-1</sup>
M <sub>2</sub>	20 Mg ha <sup>-1</sup>	20 Mg ha <sup>-1</sup>
M <sub>3</sub>	30 Mg ha <sup>-1</sup>	30 Mg ha <sup>-1</sup>

ii) Fertilizer Levels

F <sub>1</sub>	=	50 per cent of recommended NPK*	33 per cent of recommended NK
F <sub>2</sub>	=	75 per cent of recommended NPK	66 per cent of recommended NK
F <sub>3</sub>	=	100 per cent of recommended NPK	100 per cent of recommended NK

\* Recommended rate of NPK application to rice is 90-18-33 kg ha<sup>-1</sup>

The nursery sowing was done on June 5 during 1996 and June 7 during 1997. The variety of rice was HPU 2216 during 1996 and HPR 976 during 1997. The lantana was collected, chopped into 2-4 cm pieces and incorporated into soil on June 26-29 during both the years. Soil was puddled with a power tiller. Transplanting was done on July 8 during 1996 and July 12 during 1997 with 2-3 seedlings per hill at a spacing of 20 cm × 20 cm. The N was applied one-third each at 7, 30 and 45 DAT (days after transplanting). The P and K were applied during puddling as per treatments. The rice crop was harvested on October 23 during 1996 and November 7 during 1997. Average nutrient composition of lantana is given in Table 2.

Table 2. Average composition of lantana biomass (dry weight basis)

C (%)	N (%)	P (%)	K (%)	C:N ratio
50.52	2.50	0.25	1.40	20:1

## B. Wheat Crop

Wheat (cv. Aradhana) was raised as a general crop, receiving 75 per cent of recommended NPK (90N-30P-19K kg ha<sup>-1</sup>) during 1996-97, and 66 per cent of recommended NPK (80N-26P-17K kg ha<sup>-1</sup>) during 1997-98. The land was prepared manually to a depth of

10-15 cm. The N was applied in three splits, i.e. half at seeding, and one-fourth each at 30 days after sowing (DAS) and at flowering stage. During 1996-97, wheat was sown on November 23 and was harvested on May 27. During 1997-98, the crop was sown on December 25 and was harvested on May 25. Wheat was sown in lines at 22 cm apart using seed @ 100 kg ha<sup>-1</sup>.

### **3.4 Soil Observations**

Soil properties were studied during tenth cropping cycle.

#### **3.4.1 Organic Carbon (OC)**

Soil samples were collected at rice harvest for two depths, 0-0.15 and 0.15-0.30 m, in triplicate from each plot and bulk blended. One sub-sample was collected from the bulk sample for further analysis. The OC was determined in four replications for each treatment, using Walkley and Black's rapid titration method (Walkley and Black, 1934)

#### **3.4.2 Soil Physical Properties**

##### **3.4.2.1 Soil Temperature**

Soil temperature at 0.05 m depth was determined on selected days during wheat cropping season using digital thermometer (CT 802) at 06.30 and 14.30 hours.

##### **3.4.2.2 Soil Colour**

The colour of dry as well as moist soil under different lantana treatments was determined with the help of Munsell Colour Chart.

##### **3.4.2.3 Structural Properties**

*a) Bulk Density ( $\rho_b$ ):* Bulk density of whole soil, soil aggregates (2-8 mm dia) and soil clods (4-6 cm dia) was determined after rice harvest. Bulk density of whole soil was determined by using standard core method. Metal cores of 0.03 m length and 0.054 m dia were used for

collecting undisturbed soil samples of known volume. Bulk density was determined in duplicate from each plot at seven depths, i.e. 0-0.03, 0.03-0.06, 0.06-0.09, 0.09-0.12, 0.12-0.15, 0.15-0.225 and 0.225-0.30 m layers. For characterizing bulk density of 0.15-0.225 and 0.225-0.30 m, the core samples were collected at 0.17-0.20 m, and 0.25-0.28 m depths, the mid point of each soil layer.

Bulk density of soil aggregates was determined by mercury displacement method. Mass of a relatively small moisture box ( $m_1$ , g), capable of accommodating 3-4 soil aggregates (2-8 mm dia) was recorded. It was filled with mercury to the brim. Mass of 'moisture box + mercury' ( $m_2$ , g) was recorded. Soil aggregates, 3-4 in number, were oven dried, weighed and put in the moisture box filled with mercury. The aggregates were pressed into the moisture box with a transparent plastic strip having a small hole in the center to remove the mercury displaced by the aggregates in the moisture box. The mass of 'moisture box + mercury + aggregates' ( $m_3$ , g) was recorded. Then the bulk density of aggregates was determined using the following relationship :

$$\rho_b(\text{aggregates}) = m_1 / [(m_2 - m_3 - m_1) / \rho_{\text{Hg}}] \quad (3.1)$$

where,  $\rho_{\text{Hg}}$  is the density of mercury ( $13.6 \text{ g cm}^{-3}$ )

The bulk density of soil clods (4-6 cm dia) was determined by using clod saturation method of Prihar and Hundal (1971). The soil clod was oven dried, weighed ( $m_1$ , g) and saturated by placing it on a sand bath. The mass of the saturated clod was recorded ( $m_2$ , g). The bulk density of clod was determined as follows :

$$\rho_b(\text{clod}) = m_1 / [(m_2 - m_1) + (m_1 / \rho_s)] \quad (3.2)$$

where,  $\rho_s$  is the particle density of soil.

The  $\rho_s$  was determined using the standard pycnometer method. The  $\rho_b$  and  $\rho_s$  were expressed as  $\text{Mg m}^{-3}$  ( $= \text{g cm}^{-3}$ )

b) **Total Porosity ( $f$ )** : The total porosity of whole soil, soil aggregates (2-8 mm dia) and clods (4-6 cm dia) was determined at rice harvest from their particle and bulk density values, using the following relationship :

$$f = (1 - \rho_b/\rho_s) \times 100 \quad (3.3)$$

where,  $f$  is the total porosity ( per cent),  $\rho_b$  the bulk density ( $\text{Mg m}^{-3}$ ) and  $\rho_s$  the particle density ( $\text{Mg m}^{-3}$ )

c) **Air-Filled Porosity ( $f_a$ )** : Air-filled porosity was determined at frequent intervals starting after irrigation to wheat at 30 DAS (days after sowing). The determinations were made at 0-0.075 and 0.075-0.15 m soil depths. Air-filled porosity was determined using following equation :

$$f_a = f - \theta \quad (3.4)$$

where,  $f_a$ ,  $f$  and  $\theta$  refer to air-filled porosity (per cent), total porosity (per cent) and volumetric water content (per cent). Total porosity of whole soil was determined as mentioned in para (b) (eqn. 3.3). Volumetric water content was obtained by multiplying gravimetric moisture content with the bulk density of soil layer. For determining gravimetric moisture content, soil samples were taken with the help of tube auger.

d) **Water-Stable Aggregates** : For determining the water-stable aggregates (WSA), soil samples were collected from 0.15 m soil layer at 7, 30 and 60 DAT (days after transplanting), and after rice harvest. Soil samples from the soil were collected by pushing a metal core, 0.15 m long and 0.103 m dia into the puddled layer to 0.15 m depth. The wet soil samples were air

dried, gently broken into aggregates and passed through 8 mm and 2 mm sieves. The aggregates retained on 2 mm sieve were used for wet sieving. Soil samples collected after rice harvest were also prepared for wet sieving by passing them through 8- and 2-mm sieves. The wet sieving was done with Yoder's apparatus (Yoder, 1936) for half an hour by using the procedure as mentioned by Singh (1980).

The water-stable aggregates were expressed as WSA > 0.25 mm dia (per cent) and mean weight diameter (MWD, mm) (Van Bavel, 1949). The WSA > 0.25 mm dia and MWD were computed as follows:

$$\text{WSA} > 0.25\text{mm} = (\text{mass of WSA} > 0.25 \text{ mm} / \text{total mass of aggregates}) \times 100 \quad (3.5)$$

$$\text{MWD} = \sum \bar{x}_i \cdot m_i \quad (3.6)$$

where,  $\bar{x}_i$  is the mean diameter of any particular size-range of aggregates separated by sieving (mm), and  $m_i$  is the mass of aggregates in that size range as a fraction of the total mass of sample analyzed.

e) **Apparent Specific Volume** : Change in apparent specific volume (ASV) of the soil reflects the susceptibility of soil to puddling. It refers to difference between ASV after and before puddling (Bodman and Rubin, 1948). If the density of water is considered as  $1.0 \text{ Mg m}^{-3}$ , ASV is computed as :

$$\text{ASV} = w + 1/\rho_s \quad (3.7)$$

where,  $w$  is the gravimetric moisture content (per cent, mass basis) at saturation and  $\rho_s$  the particle density ( $\text{Mg m}^{-3}$ ) of the soil.

The ASV was determined before and after puddling of soil. Before puddling,  $1 \text{ m}^2$  area in the center of each plot was provided with bunds and saturated with water. The gravimetric

water content of saturated soil (0-0.15 m) was determined in triplicate to compute the ASV. Similarly, gravimetric water content was determined for the same soil layer 3-d after puddling. Change in apparent specific volume ( $\Delta ASV$ ) was determined by the following relationship :

$$\Delta ASV = ASV_{ap} - ASV_{bp} \quad (3.8)$$

where,  $ASV_{ap}$  and  $ASV_{bp}$  refer to apparent specific volume after puddling and before puddling of soil.

**f) Puddling Index :** Puddling index was determined by the method given by Sinha (1964). Samples of puddled soil were collected in 8 cm long beakers immediately after puddling in each plot. Depth of the soil suspension ( $l_1$ , cm) was measured in each beaker. The suspension was allowed to settle for 24 hours. The supernatant liquid was then discarded and the depth of settled soil was recorded ( $l_2$ , cm). The puddling index was computed as follows

$$\text{Puddling index} = (l_2 / l_1) \times 100 \quad (3.9)$$

**g) Coefficient of Linear Extensibility (COLE) :** The COLE is a measure of the potential volume change of a soil upon its wetting or drying and swelling and shrinkage. The soil with high COLE have management problems. The soil with a COLE value of 0.09 or greater are placed in the Vertic sub-group. COLE was computed as :

$$\text{COLE} = (\rho_{bd} / \rho_{bm})^{1/3} - 1 \quad (3.10)$$

where,  $\rho_{bd}$  and  $\rho_{bm}$  are bulk densities of dry and moist soil, respectively.

Metal cores, 0.03 m long and 0.054 m in dia, greased from inside, were used to collect soil samples from the field for determination of COLE. Three soil cores were collected from the surface layer of each plot, when the soil was wet. The mass of 'empty core' and 'core + wet soil' were recorded. The soil-core was dried gradually at room temperature. When the soil core

left the walls of the metal core, it was taken out of core and dried in hot air oven. The mass of the oven-dried soil core was recorded. Soil core was then immersed in molten paraffin wax with the help of a thin thread tied to the core, to make the soil core water proof. The mass of oven-dried soil core coated with thin layer of paraffin wax was recorded to compute the volume of wax. The volume of wax-coated soil core was determined by placing the core in a beaker containing water and noting the volume of water displaced by the core.

The moist ( $\rho_{bm}$ ) and dry ( $\rho_{bd}$ ) bulk densities were computed as follows :

$$\rho_{bm} = \text{Mass of oven-dry soil core (g)} / \text{Volume of metal core (cm}^3\text{)} \quad (3.11)$$

$$\rho_{bd} = \text{Mass of oven-dry soil core (g)} / \text{Volume of oven-dry soil core (cm}^3\text{)} \quad (3.12)$$

While computing the volume of oven-dry soil core by water displacement method, as mentioned above, the volume of wax coated on the soil core was subtracted from the volume of water displaced. The volume of wax ( $V_{wax}$ , cm<sup>3</sup>) coated on the soil core was calculated as follows :

$$V_{wax} = \frac{\text{Mass of wax coated on soil core} - \text{Mass of oven-dried soil core without wax}}{\text{density of wax}} \quad (3.13)$$

The density of the paraffin wax was 0.50 g cm<sup>-3</sup>.

**h) Soil Cracking :** Soil cracking was evaluated in a 1-m × 1-m area in the center of each plot by the method outlined by Sharma *et al.* (1995). Cracks were divided into five classes of width <5, 5-10, 10-15, 15-20 and >20 mm. The length of cracks was measured with the help of a thread spread over the entire length of a given crack-class. The average depth of each crack-class was determined by inserting a 1.5 mm dia wire at several locations along the entire length of the crack.

The volume ( $V$ ,  $m^3$ ) and surface area ( $SA$ ,  $m^2$ ) of the crack was computed by using the following equations :

$$V = \sum 0.5 \bar{w} \times d \times l \quad (3.14)$$

$$SA = \sum 2c \times l \quad (3.15)$$

$$c = [(0.5 \bar{w})^2 + d^2]^{1/2} \quad (3.16)$$

where,  $\bar{w}$ ,  $d$  and  $l$  refer to mean width (m), depth (m) and length (m) of a given crack-class.

**i) Clod Size Distribution :** Clod-size distribution was determined after the soil was prepared for sowing of wheat. Three sieves were fabricated with the help of steel wire (1.5 mm dia ), each having square holes of 2, 4 and 6 cm, respectively. About 10 kg of soil collected from the tilled layer (0-0.15 m) at field moisture content was passed through the nest of three sieves (6, 4 and 2 cm ). The mass of clods retained on each sieve was recorded and corrected to oven-dry equivalent basis by determining its gravimetric moisture content. The clod-size distribution was expressed on per cent basis.

**j) Soil Penetration Resistance (SPR) :** Soil penetration resistance refers to the resistance offered by the soil to a metal probe (representing plant roots ) pushed into soil. The SPR as a function of soil moisture content was determined at 0.075 and 0.15 m soil depths at frequent intervals starting at 30 DAS when wheat was irrigated. About ten observations were made in each plot at each depth for computing the average SPR. The SPR was determined with the help of a Proctor penetrometer having 0.18 m long probe with a flat tip of  $2.61 \times 10^{-4} m^2$  surface area.

For determining SPR at 0.075- and 0.15 m depths, auger holes (with tube auger) were made to the required depths. The probe of the penetrometer was inserted into the hole and

pushed 0.03 m into the soil. After recording the SPR value, soil sample from the same soil layer (0.03 m) was collected with the help of a tube auger for determining gravimetric moisture content.

The SPR versus gravimetric moisture content values were plotted. The relationship was used to determine 'Non-Limiting Water Range' (NLWR) values.

#### 3.4.2.4 Hydraulic Properties

a) *Soil-water retention Curve* : Soil-water retention curve was determined during rice (30 DAT), after rice harvest and 30 DAS of wheat (after applying the first irrigation). Soil-core samples, 0.03 m long and 0.054 m dia were collected in triplicate from each plot in the middle of 0-0.075 m soil layer with the help of metal cores. The soil-water retention curve was determined using pressure plate apparatus (Soil Moisture Equipment Co., Santa Barbara, USA).

These data were used to determine pore-size distribution using capillary-rise equation as follows :

$$h = 2 \Gamma \text{Cos } \theta / \rho_w g r \quad (3.17)$$

$$\text{or } h = 4 \Gamma \text{Cos } \theta / \rho_w g d \quad (3.18)$$

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

Soil-water contact angle is so small that  $\text{Cos } \theta$  is practically equal to 1, and at 20°C, the values of other parameters are :

$$\Gamma = 72.75 \text{ dynes cm}^{-1}$$

$$\rho_w = 0.998 \text{ g m}^{-3}$$

$$g = 981 \text{ cm s}^{-2}$$

Using these values, eqn. (3.18) reduces to

$$h = 0.298 / d \cong 0.3 / d \quad (3.19)$$

Using eqn. (3.19), the suction values equivalent to different pore sizes were computed.

The volume of each pore range was then calculated by determining the volume of water retained by the soil between the equivalent suction values. Based on these values, volume of transmission pores ( $> 50 \mu\text{m}$ ), water storage pores ( $50\text{-}0.5 \mu\text{m}$ ), and residual pores ( $< 0.5 \mu\text{m}$ ) were determined (Greenland, 1979).

**b) Plant-Available Water Capacity (PAWC) :** The PAWC was determined from the soil-moisture characteristic curve for different treatments, both, at rice harvest and 30 DAS of wheat. The PAWC was determined as follows :

$$\text{PAWC} = \text{FC} - \text{PWP} \quad (3.20)$$

where, FC is the field capacity, i.e. moisture retained at 30 kPa suction, and PWP the permanent wilting point, i.e. moisture retained at 1500 k Pa suction.

**c) Soil Infiltrability :** The infiltration behavior of soil under different treatments was studied at rice and wheat harvest using double ring infiltrometer. The infiltrometers were pushed into the ground to a depth of 0.10 m. A pointed nail was fixed inside the inner infiltrometer at about 0.10 m height from the surface of soil. Same water level was maintained in, both, the inner and outer infiltrometers. The volume of water infiltrated into soil as a function of time was measured by replacing the water receded inside the inner infiltrometer with the help of measuring cylinder.

The depth of the water infiltrated was computed by dividing the volume with the cross-section area of the inner infiltrometer. Regular determinations were made at periodical intervals until the steady state condition of water flux was reached. The data was plotted as infiltration rate and cumulative infiltration versus time.

**d) Saturated Hydraulic Conductivity (Ks) :** The Ks was determined after the harvest of rice and wheat crops by constant water head method of Klute (1965). Undisturbed soil cores were collected in triplicate from each plot in metal cores of 0.03 m length and 0.054 m dia. The Ks was determined as follows :

$$K_s = Q L / A T(L + H) \quad (3.21)$$

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

**e) Soil-Water Contact Angle :** Air-dry soil passed through 2 mm sieve was packed into graduated 0.70 m long and 10 mm dia glass tubes, closed at one end with a piece of muslin cloth. For uniform packing, the soil was poured into the entire length of glass tube in one lot. The glass tube was tapped for one hundred times for the settling of soil particles. The final length of the soil was about 0.55 m. Four such soil columns per treatment were prepared in this way.

The glass tube was placed vertically in metallic stands. Two glass tubes were dipped 10 mm deep in ethanol and the other two in distilled water contained in 100 ml beakers. The height of capillary rise of ethanol and water in glass tubes was recorded after 24 hours. The

contact angle was determined by using capillary-rise equation as follows :

$$h = 2 \Gamma \text{Cos } \theta / \rho g r \quad (3.22)$$

$$\text{or } r = 2 \Gamma \text{Cos } \theta / \rho g h \quad (3.23)$$

where,  $h$  is the height of capillary rise (cm),  $\Gamma$  the surface tension of liquid ( $\text{dynes cm}^{-1}$ ),  $\theta$  the contact angle in degrees,  $\rho$  the density of liquid ( $\text{g m}^{-3}$ ),  $g$  the acceleration due to gravity ( $\text{cm s}^{-2}$ ) and  $r$  the average radius of capillaries (cm).

The value of  $r$  was calculated from eqn. (3.23) by using data on capillary rise of ethanol, assuming soil-ethanol contact angle to be zero. Then  $\text{Cos } \theta$  for ethanol is equal to 1. For ethanol the capillary-rise equation (3.23) would be

$$\begin{aligned} r &= 2 \times 22.32 \times 1 / 0.789 \times 981 \times h_{(\text{ethanol})} \\ &= 0.05767 / h_{(\text{ethanol})} \end{aligned} \quad (3.24)$$

The value of  $r$  computed from eqn. (3.24) was used to determine the soil-water contact angle ( $\theta$ ), assuming pore-size distribution in soil columns used for capillary rise of water and ethanol as identical. The capillary-rise equation (3.23) for water would be

$$\begin{aligned} r &= 2 \times 72.75 \text{Cos}\theta / 0.998 \times 981 \times h_{(\text{water})} \\ \text{or } h_{(\text{water})} &= 2 \times 72.75 \text{Cos}\theta / 0.998 \times 981 \times r \\ \therefore \text{Cos } \theta &= 6.729 \times r h_{(\text{water})} \\ \text{hence } \theta &= \text{Cos}^{-1}(6.729 r h_{(\text{water})}) \end{aligned} \quad (3.25)$$

**f) Drying Pattern :** The observations on drying pattern of soil were studied during the standing crop of rice after giving the last irrigation, and continued after rice harvest. Mercury

tensiometers were placed in duplicate at 0.15 and 0.30 m depths in each plot in one replication. Daily observations on the soil matric potential were made at 10.00 h and continued until the mercury in tensiometer stopped rising. A regular vigil on the appearance of surface cracks was maintained. Immediately at the appearance of hair-line cracks at soil surface, gravimetric moisture content of 0-0.15 m soil layer was determined. The plots were allowed to dry for the development of surface cracks.

#### **3.4.2.5 Mechanical Properties**

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

The consistency limits of experimental soil were determined after the harvest of rice crop. Soil samples were collected from 0-0.15 m soil layer from each plot. They were air-dried, passed through 2 mm sieve and analyzed for different soil consistency limits as follows :

i) **Liquid Limit (LL)** : Liquid limit was determined according to ASTM (American Society for Testing Materials) procedure using Casagrande's liquid limit device. About 200 g soil sample was taken to make stiff paste with distilled water. About 30 g of this paste was put in the cup of the device so as to form a 0.01 m thick layer of paste. The cup was pre-adjusted to 0.01 m drop. With the help of a groove tool, 0.01 m groove was cut at the center of the paste. The crank was turned at 2 revolutions per second and number of taps required to close the

groove at the bottom was recorded. The procedure was repeated several times at different moisture contents. Five observations of number of taps (varying between 18 and 32) and the gravimetric moisture of soil were recorded. Observations with number of taps <18 or >32 were discarded. The liquid limit (per cent, mass basis) was determined as follows :

$$LL = w_n (N / 25)^{0.12} \quad (3.26)$$

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

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

iii) **Shrinkage limit (SL)** : Saturation paste of soil was prepared. The paste was transferred into small, greased shrinkage dishes of known volume with gentle tapping for exclusion of air bubbles, if any. The top of the shrinkage dish was cleared off excess soil by means of a straight edge. The mass of 'dish + soil' was recorded. Dish containing soil was oven dried, and the mass of 'dish + oven-dry soil' was recorded. These data were used to compute the moisture content of saturation paste. The volume of dried soil cakes was determined by mercury displacement method as mentioned in para 3.4.2.1 (d). The shrinkage limit (per cent, mass basis) was calculated as follows :

$$SL = w_i - [(v_i - v_s) \rho_w / w_d] \times 100 \quad (3.27)$$

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

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

$$\text{PI} = \text{LL} - \text{PL} \quad (3.28)$$

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

$$\text{Friability Range} = \text{PL} - \text{SL} \quad (3.29)$$

b) **Energy Required for Land Preparation** : The plots after the harvest of rice crop were manually prepared for sowing of wheat. The time required to dig and pulverize each plot was recorded. The energy required to prepare each plot was computed by considering the energy of an adult worker equal to  $1.96 \text{ MJ human h}^{-1}$ . Energy required in land preparation  $\text{ha}^{-1}$  (E,  $\text{GJ ha}^{-1}$ ) was computed as follows :

$$E = 1.96 \times 10^6 \times t / A \quad (3.30)$$

where,  $t$  is the time (h) required to prepare the plot having area  $A$  ( $\text{m}^2$ ).

c) **Clod Breaking Strength** : Clod breaking strength (CBS) refers to the energy required to break the clods. The CBS was determined at different moisture contents using the apparatus developed by Sharma and Bhagat (1993). About thirty clods (4-6 cm dia) collected per treatment were saturated on a sand bath and allowed to dry under laboratory conditions for varying periods. At regular intervals, a set of five clods was transferred to a polyethylene bag,

sealed and kept for 2-3 days to homogenize the moisture within the clod. The clods were then tested for CBS. The moisture content of each broken clod was determined gravimetrically.

### 3.4.3 Non-Limiting Water Range :

The 'non-limiting water range' (NLWR) concept was given by Letey (1985) for evaluating the soil physical conditions with respect to plant growth. It is a single value index. Higher the NLWR, better is the soil physical conditions.

The NLWR was computed as the difference between the soil moisture content at which the air-filled porosity ( $f_a$ ) was 10 per cent (upper limit of moisture content)[Letey (1985) used ODR (oxygen diffusion rate) instead of air-filled porosity] and the moisture content at which the soil penetration resistance (SPR) was 2 MPa (lower limit of moisture content) at 0.15 m soil depth. The value of 2 MPa SPR was used based on our previous studies (Bhushan and Sharma, 1997). At this SPR, the RMD of wheat was reduced to about half. The wheat crop was irrigated at 30 DAS. The  $f_a$  and SPR were determined frequently at regular intervals by using the procedure as described in para 3.4.2.3 (c) and 3.4.2.3 (j), respectively.

A hole was made upto 0.15 m depth in soil with a tube auger. The SPR was determined with proctor penetrometer. Soil sample was extracted from 0.15-0.18 m depth with the tube auger to determine the gravimetric moisture content and  $f_a$ .

## 3.5 Plant Observations :

### 3.5.1 Crop Yields :

Grain and straw yields of rice and wheat were recorded at crop harvest. However, during *khariif*, 1996 due to, damage caused to rice crop by blast incidence, total biomass was recorded at crop harvest.

### 3.5.2 Root Studies

Root system of wheat was studied, both quantitatively and qualitatively. For studying the spatial distribution, the intact root-system was extracted from soil with the help of pin-boards, and for determining root mass density, the roots were collected with the help of metal core. Representative wheat plants were selected in each plot for root sampling.

**3.5.2.1 *Spatial Distribution of Roots* :** A pin-board, 0.45 m long and 0.30 m wide, was fabricated by welding 0.15 m long iron nails on galvanized iron sheet (10 gauge) at 0.05-m grid. A handle was provided at the upper end of pin-board for its handling. A trench, about 0.50 m deep, was dug 0.075 m apart on one side of the crop row. The pin-board was hammered into the side of the profile containing root system. The soil block held on the pin-board was dug out. The soil block was kept under water for 24 hours and then washed free of soil with fine jet of water. The roots were air-dried on board and photographed.

**3.5.2.2 *Root Mass Density and Shoot/Root Ratio* :** Soil core samples (0.15 m long and 0.103 m dia) were collected at 0 - 0.15 and 0.15 - 0.30 m depths from each treatment in all the three replications. The roots were washed on 70 mesh sieve with water jet and dried in oven at 70° C for three days to determine the root mass. The root mass density (RMD) was calculated as root mass per unit soil volume.

Before collecting soil-cores, the shoot was cut at soil surface, oven-dried at 70° C and weighed. These data were used to compute shoot /root ratio.

### **3.6 Distinguishing between effects of physical and chemical properties of soil on wheat yield**

An attempt was made to distinguish between the effects of changes in physical and chemical properties of soil due to lantana additions on wheat crop. For this, 10 kg soil sample was collected from the surface layer (0-0.15 m) of each plot after tilling the plots for wheat sowing. The soil sample was crushed and passed through 2 mm sieve to eliminate the differences in physical properties of soil. Each sample was packed in polyethylene bags 0.30 m long and 0.2 m dia. Equal amounts of recommended NPK on soil-weight basis was mixed with soil in each bag. The polybags were kept in a plot near the experimental site and were randomized similar to field plots. Six seeds of wheat (cv. Aradhana) were dibbled in each bag and an amount of 4-cm water was added. After germination the seedlings were thinned to two per bag. Each polybag was subsequently irrigated with 2-cm water on alternate days. The wheat plants were harvested at maturity. The grain and straw yields were recorded. The per cent increase in grain yield with a given treatment over control in the field and polybags was computed. The increase in grain yield in the field was considered due to the improvement in both, chemical and physical properties, and in the polybags due to chemical properties only. Hence, the difference in yield increases in the field and polybags was considered to be due to improvement in soil physical properties.

### **3.7 Statistical Analysis :**

The data were analyzed statistically using standard statistical procedures.



## RESULTS

## IV RESULTS

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The results pertaining to the study, “Changes in soil physical properties and crop yields with long-term additions of *Lantana camara* biomass in rice-wheat cropping,” have been presented in this chapter under the following heads :

### 4.1 Soil Organic Carbon

### 4.2 Soil Physical Properties

#### 4.2.1 Soil Colour

#### 4.2.2 Soil Temperature

#### 4.2.3 Structural Properties

#### 4.2.4 Hydraulic Properties

#### 4.2.5 Mechanical Properties

### 4.1 Crop Studies

#### 4.3.1 Root Studies

#### 4.3.2 Shoot /root Ratio

#### 4.3.3 Crop Yields

### 4.2 Non-Limiting Water Range

### 4.3 Distinguishing Between Effects of Physical and Chemical Properties of Soil on wheat Yield ✓

## 4.1 Soil Organic Carbon

Lantana additions significantly increased the organic carbon (OC) content of surface (0-0.15 m) and subsurface (0.15-0.30 m) soil layers (Table 3). The OC content of soil treated with 0, 10, 20 and 30 Mg ha<sup>-1</sup> lantana was 11.1, 12.5, 13.0 and 14.2 g kg<sup>-1</sup> of soil, respectively, in 0-0.15 m soil layer, and 7.6, 8.9, 9.6 and 10.6 g kg<sup>-1</sup> of soil, respectively, in 0.15-0.30 m soil layer. Thus, application of lantana to rice @ 10, 20 and 30 Mg ha<sup>-1</sup> over a period of ten years

Table 3 Effect of ten annual applications of lantana biomass on organic carbon (OC) content of soil determined at rice harvest

Treatment (Lantana, Mg ha <sup>-1</sup> )	OC (g kg <sup>-1</sup> of soil)			OC content (Mg ha <sup>-1</sup> )***		Biomass added in 10 years (Mg ha <sup>-1</sup> )		OC retained (Mg ha <sup>-1</sup> )			Per cent OC Retained over control	
	0-0.15 m	0.15-0.30 m	0-0.15 m	0.15-0.30 m	Lantana*	OC**	0-0.15 m	0.15-0.30 m	0-0.15 m	0.15-0.30 m	0-0.15 m	0.15-0.30 m
	0	11.1	7.6	23.6	16.4	0	0	-	-	-	-	-
10	12.5	8.9	26.6	19.2	36	18.2	3.0	2.8	16.5	15.4		
20	13.0	9.6	27.7	20.7	72	36.2	4.1	4.3	11.3	11.8		
30	14.2	10.6	30.3	22.9	108	54.4	6.7	6.5	12.3	11.9		
LSD (P = 0.05)	2.0	2.2	-	-	-	-	-	-	-	-	-	-

\* Water content of fresh lantana = 64.0 per cent

\*\*OC of lantana biomass = 50.5 per cent

\*\*\*For both the layers, OC content is calculated on the basis of mass of soil of control treatment

increased the OC in 0-0.15 m soil layer by 12.6, 17.6 and 27.9 per cent, and in 0.15-0.30 m soil layer by 17.1, 26.3 and 39.5 per cent over control, respectively.

The total amount of OC added to 0-0.15 m soil layer, corresponding to 10, 20 and 30 Mg ha<sup>-1</sup> year<sup>-1</sup> for 10 years, was 18.2, 36.2 and 54.6 Mg ha<sup>-1</sup>. Of this, 3.0, 4.1 and 6.7 Mg OC ha<sup>-1</sup> was retained in 0-0.15 m soil layer, and 2.8, 4.3 and 6.5 Mg ha<sup>-1</sup> was retained in 0.15-0.30 m soil layer. (The amount of OC retained in soil was determined by subtracting OC in control plots from that in *lantana*-treated plots). Thus, 17, 11 and 12 per cent of OC was retained in 0-0.15 m soil layer, and 15, 12 and 12 per cent of OC was retained in 0.15-0.30 m layer. Considering 0-0.30 m soil layer as a whole, 32, 23 and 24 per cent of the added OC was retained in soil.

## 4.2 Soil Physical Properties

### 4.2.1 Soil Colour

The colour of the soil became darker with the use of *lantana* (Table 4). The soil colour changed from 10 YR 6/6 (brownish yellow) in control to 10 YR 6/4 (light yellowish brown) in *lantana*-treated plots when observed for dry soil samples. The colour of moist soil samples changed from 10 YR 5/4 (yellowish brown) in control to 10 YR 5/3 (brown) in plots treated with 10 Mg *lantana* ha<sup>-1</sup>, and 10 YR 4/3 (dark brown) in plots treated with 20 and 30 Mg *lantana* ha<sup>-1</sup>.

### 4.2.2 Soil Temperature

Soil temperature were recorded at 0.05 m depth on selected days during wheat growth. Soil temperatures recorded at 06.30 h (minimum) and 14.30 h (maximum) on December 30,

1997 (one of the coldest days) are shown in Table 4. Both, minimum as well as maximum temperatures, were lowest in control and increased with the amount of lantana applied. The minimum temperature was 5.4°C in control and increased to 5.6, 5.7 and 5.7°C in plots treated with 10, 20 and 30 Mg lantana ha<sup>-1</sup>, respectively. The corresponding values of maximum soil temperature were 11.9, 12.2, 12.3 and 12.5°C, respectively.

Table 4 Effect of ten annual applications of lantana on soil colour determined at rice harvest

Treatment (Lantana, Mg ha <sup>-1</sup> )	Soil Colour		Soil Temperature (°C)	
	Dry	Moist	Max.	Min.
0	10 YR 6/6 (Brownish yellow)	10 YR 5/4 (Yellowish brown)	11.9	5.4
10	10 YR 6/4 (Light yellowish brown)	10 YR 5/3 (Brown)	12.2	5.6
20	10 YR 6/4 (Light yellowish brown)	10 YR 4/3 (Dark brown)	12.3	5.7
30	10 YR 6/4 (Light yellowish brown)	10 YR 4/3 (Dark brown)	12.5	5.7

### 4.2.3 Structural Properties

**4.2.3.1 Soil Aggregation :** Addition of lantana @ 10, 20 and 30 Mg ha<sup>-1</sup> improved soil aggregation, evaluated and expressed as mean weight diameter (MWD, mm) and water stable-aggregates > 0.25 mm dia (WSA, per cent) (Table 5).

MWD as well as WSA at any time during cropping season of rice were significantly ( $P = 0.05$ ) higher in lantana-treated plots than in control plots. The MWD in plots treated with lantana @ 0, 10, 20 and 30 Mg ha<sup>-1</sup> at 7 DAT (days after transplanting) was 0.75, 0.95, 1.27 and 1.75 mm; at 30 DAT was 0.92, 1.43, 1.57 and 2.79 mm; at 60 DAT was 1.25, 1.75, 2.10 and 2.86 mm; and at harvest was 1.93, 2.73, 2.81 and 3.64 mm, respectively. The MWD at 7

DAT was 27, 69 and 133 per cent of control; at 30 DAT was 55, 71 and 203 per cent of control; at 60 DAT was 40, 68 and 129 per cent of control; and at harvest was 41, 46 and 89 per cent of control. The WSA in plots treated with 0, 10, 20 and 30 Mg ha<sup>-1</sup> lantana at 7 DAT was 33.6, 42.2, 57.8 and 64.2 per cent; at 30 DAT was 36.2, 53.5, 64.2 and 73.9 per cent; at 60 DAT was 45.0, 60.8, 67.4 and 77.9 per cent; and at rice harvest was 62.0, 71.5, 78.4 and 86.8 per cent, respectively.

Table 5 Effect of ten annual applications of lantana biomass on water-stable aggregates during rice cropping season

Treatment (Lantana, Mg ha <sup>-1</sup> )	MWD (mm) at DAT*				WSA > 0.25 mm dia (%) at DAT			
	7	30	60	at harvest	7	30	60	at harvest
0	0.75	0.92	1.25	1.93	33.6	36.2	45.0	62.0
10	0.95	1.43	1.75	2.73	42.2	53.5	60.8	71.5
20	1.27	1.57	2.10	2.81	57.8	64.2	67.4	78.4
30	1.75	2.79	2.86	3.64	64.2	73.9	77.9	86.8
LSD (P = 0.05)	0.26	0.29	0.28	0.28	11.0	8.8	11.1	8.1

\* DAT = Days after transplanting

**4.2.3.2 Bulk density :** Bulk density of soil determined at rice harvest at regular depth intervals upto 0.30 m depth is shown in Fig. 1. (Appendix I). Bulk density in 0-0.30 m depth varied between 1.41 and 1.44 Mg m<sup>-3</sup> in control (M<sub>0</sub>), between 1.25 and 1.41 in plots treated with 10 Mg lantana ha<sup>-1</sup> (M<sub>1</sub>), between 1.16 and 1.38 Mg m<sup>-3</sup> in plots treated with 20 Mg lantana ha<sup>-1</sup> (M<sub>2</sub>), and between 0.99 and 1.37 Mg m<sup>-3</sup> in plots treated with 30 Mg lantana ha<sup>-1</sup> (M<sub>3</sub>). These data showed that bulk density in control was highest at all soil depths upto 0-0.30 m. Additions of lantana significantly decreased bulk density, and the decrease was proportional

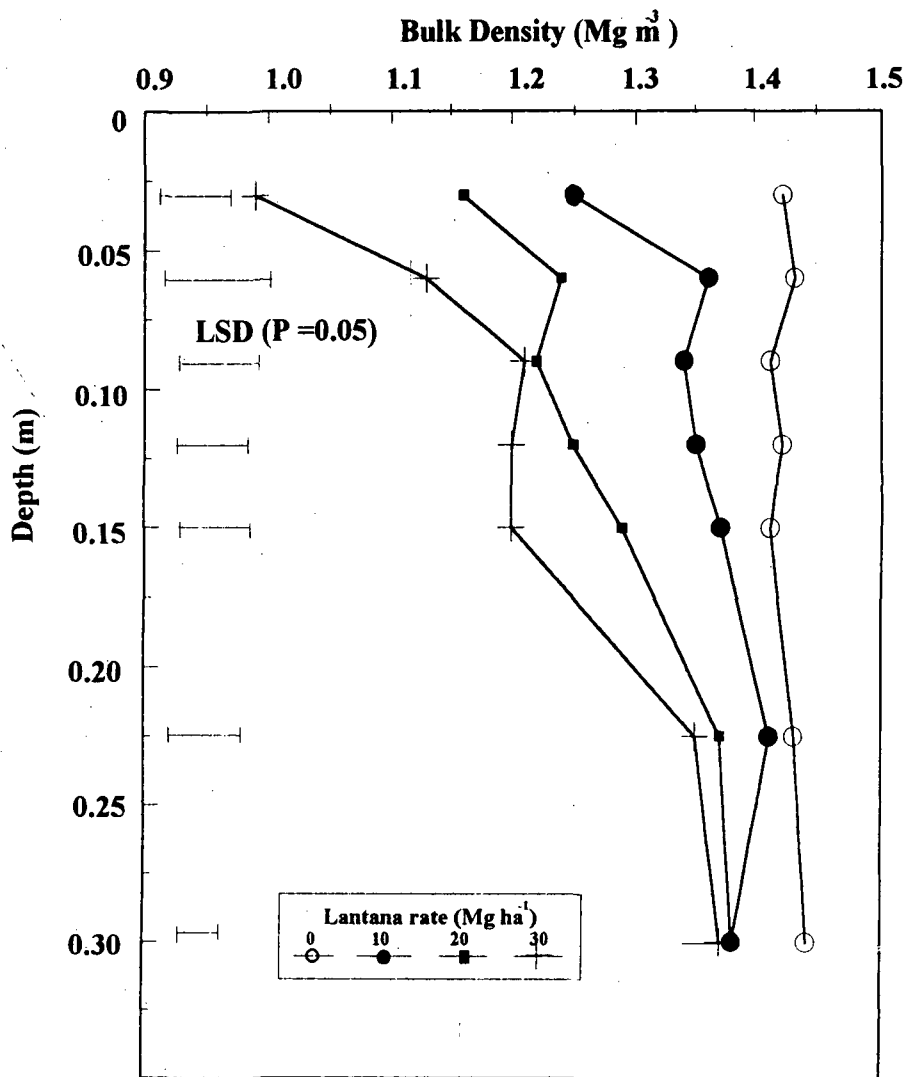


Figure 1. Effect of ten annual applications of lantana biomass on the bulk density of soil at rice harvest

to the amount of lantana added. Thus, at any depth within 0-0.30 m, profile bulk density followed the trend of  $M_0 > M_1 > M_2 > M_3$  treatment.

On an average, the bulk density of plough layer (0-0.15 m) was reduced by 6, 13 and 19 per cent, and of subsoil (0.15-0.30 m) by 2, 4 and 6 per cent over control with the addition of lantana @ 10, 20 and 30 Mg ha<sup>-1</sup>, respectively (Table 6). The differences in bulk density with different lantana treatments were statistically significant ( $P = 0.05$ ).

Bulk density of soil aggregates (2-8 mm dia) as well as clods (4-6 cm dia) was also reduced significantly by lantana treatments (Table 6). The reduction in bulk density of soil aggregates was 7, 11 and 14 per cent, and of clods was 4, 7 and 9 per cent over control with 10, 20 and 30 Mg ha<sup>-1</sup>, respectively.

Table 6 Effect of ten annual applications of lantana biomass on bulk density of soil, soil aggregates and clods at rice harvest

Treatment (Lantana, Mg ha <sup>-1</sup> )	Bulk Density (Mg m <sup>-3</sup> )			
	0-0.15 m soil	0.15-0.30 m soil	Soil aggregates (2-8 mm dia)	Clods (4-6 cm dia)
0	1.42	1.44	1.60	1.49
10	1.33	1.41	1.49	1.43
20	1.23	1.38	1.43	1.38
30	1.15	1.36	1.37	1.35
LSD ( $P = 0.05$ )	0.06	0.04	0.05	0.04

**4.2.3.3 Total Porosity :** The values of total porosity of soil were determined at rice harvest by using the relationship between total porosity, bulk density and particle density. The particle density ( $\rho_s$ ) was determined in all the experimental plots. Since there was no substantial difference in the values of  $\rho_s$  in different plots, an average value of  $\rho_s$ , equal to 2.44 ( $\pm 0.02$ ) Mg

$\text{m}^{-3}$ , was used for computing total porosity. The values of total porosity of whole soil (0-0.15 m), soil aggregates (2-8 mm dia) and clods (4-6 cm dia) as influenced by lantana treatment are given in Table 7.

Addition of lantana significantly increased the total porosity of soil in plough layer, soil aggregates and soil clods. The increase in total porosity with 10, 20 and 30 Mg lantana  $\text{ha}^{-1}$  over the control was about 9, 11 and 27 per cent in 0-0.15 m soil layer, 13, 20 and 27 per cent in soil aggregates, and 6, 12 and 15 per cent in soil clods, respectively.

Table 7 Effect of ten annual applications of lantana biomass on total porosity of soil, soil aggregates and clods at rice harvest

Treatment (Lantana, Mg $\text{ha}^{-1}$ )	Total porosity (%)		
	at 0-0.15 m	Soil aggregates (2-8 mm dia)	Clods (4-6 cm dia)
0	41.80	34.42	38.93
10	45.49	38.93	41.39
20	49.59	41.39	43.44
30	52.87	43.85	44.67
LSD (P = 0.05)	1.13	2.12	1.61

**4.2.3.4 Pore-size Distribution :** The pore-size distribution was computed from soil-water retention data during rice cropping (30 DAT), at rice harvest and during wheat season (at 30 DAS), and are shown in Fig 2 (Appendix II). The total porosity in untreated control was 62.3 per cent during rice cropping, 51.4 per cent at rice harvest, and 52.4 per cent during wheat season. It increased to 62.5, 63.9, and 64.1 per cent during rice, 53.6, 56.0 and 57.3 per cent at rice harvest, and 61.2, 62.5 and 64.3 per cent during wheat season with 10, 20, and 30 Mg lantana  $\text{ha}^{-1}$ , respectively.

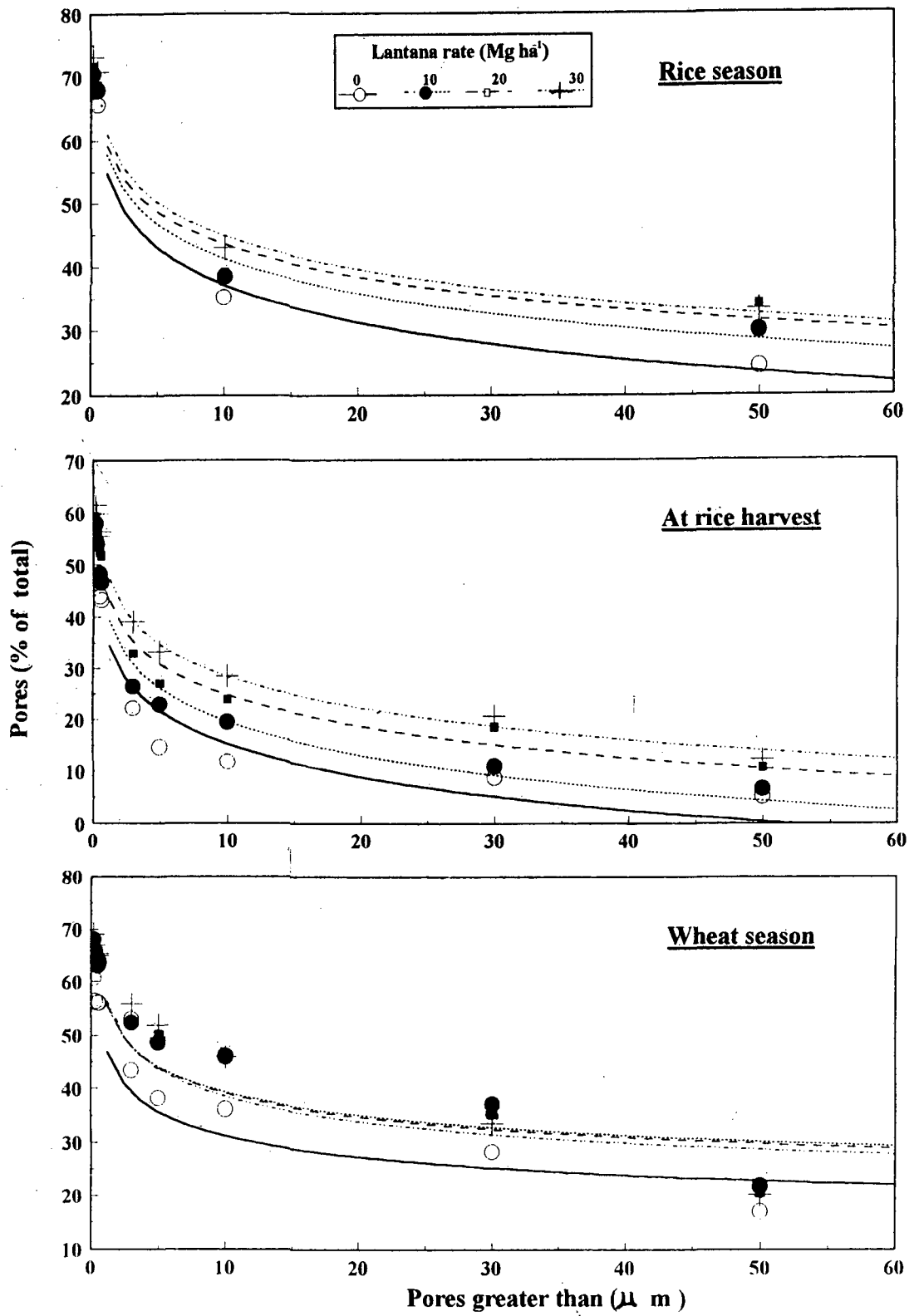


Figure 2. Effect of ten annual applications of lantana biomass on pore-size distribution in 0-0.075 m soil layer

Pores were classified according to the classification given by Greenland (1979). The transmission ( $> 50 \mu\text{m}$ ), storage ( $0.5-50 \mu\text{m}$ ) and residual pores ( $< 0.5 \mu\text{m}$ ) in control and treated plots are shown in Fig 3 (Appendix III). During rice cropping season, the transmission pores increased by 20-37 per cent over control while the storage and residual pores decreased by 7-15 and 6-15 per cent, respectively, with lantana treatments. At rice harvest, transmission and storage pores increased by 27-136 per cent and 7-14 per cent, respectively, while residual pores decreased by 8-24 per cent over control, with lantana treatments. During wheat season, transmission as well as storage pores increased by 22-29 and 6-16 per cent, respectively, while the residual pores decreased by 16-21 per cent over control.

**4.2.3.5 Soil Penetration Resistance :** Soil penetration resistance (SPR), determined at 30 DAS (days after sowing) of wheat (after irrigation) and thereafter at frequent intervals at 0.075 and 0.15 m soil depths, was significantly affected by lantana treatments and soil moisture content. The SPR at a given moisture content was highest in control plots, and decreased progressively with the increase in amount of lantana added. Similar trend was observed at 0.075 and 0.15 m soil depths (Fig. 4, Appendix IV). The SPR (MPa) was linearly, negatively and significantly correlated with moisture content ( $\theta$ , per cent), at each levels of lantana addition at both the soil depths as follows:

At 0.075 m soil depth : ( $n = 35, 23.0 \leq \theta \leq 41.0$ )

$$\text{SPR (M}_0\text{)} = 3.03 - 0.062 \theta; \quad r = -0.805^{**} \quad (4.1)$$

$$\text{SPR (M}_1\text{)} = 2.97 - 0.062 \theta; \quad r = -0.891^{**} \quad (4.2)$$

$$\text{SPR (M}_2\text{)} = 2.93 - 0.096 \theta; \quad r = -0.915^{**} \quad (4.3)$$

$$\text{SPR (M}_3\text{)} = 2.87 - 0.096 \theta; \quad r = -0.790^{**} \quad (4.4)$$

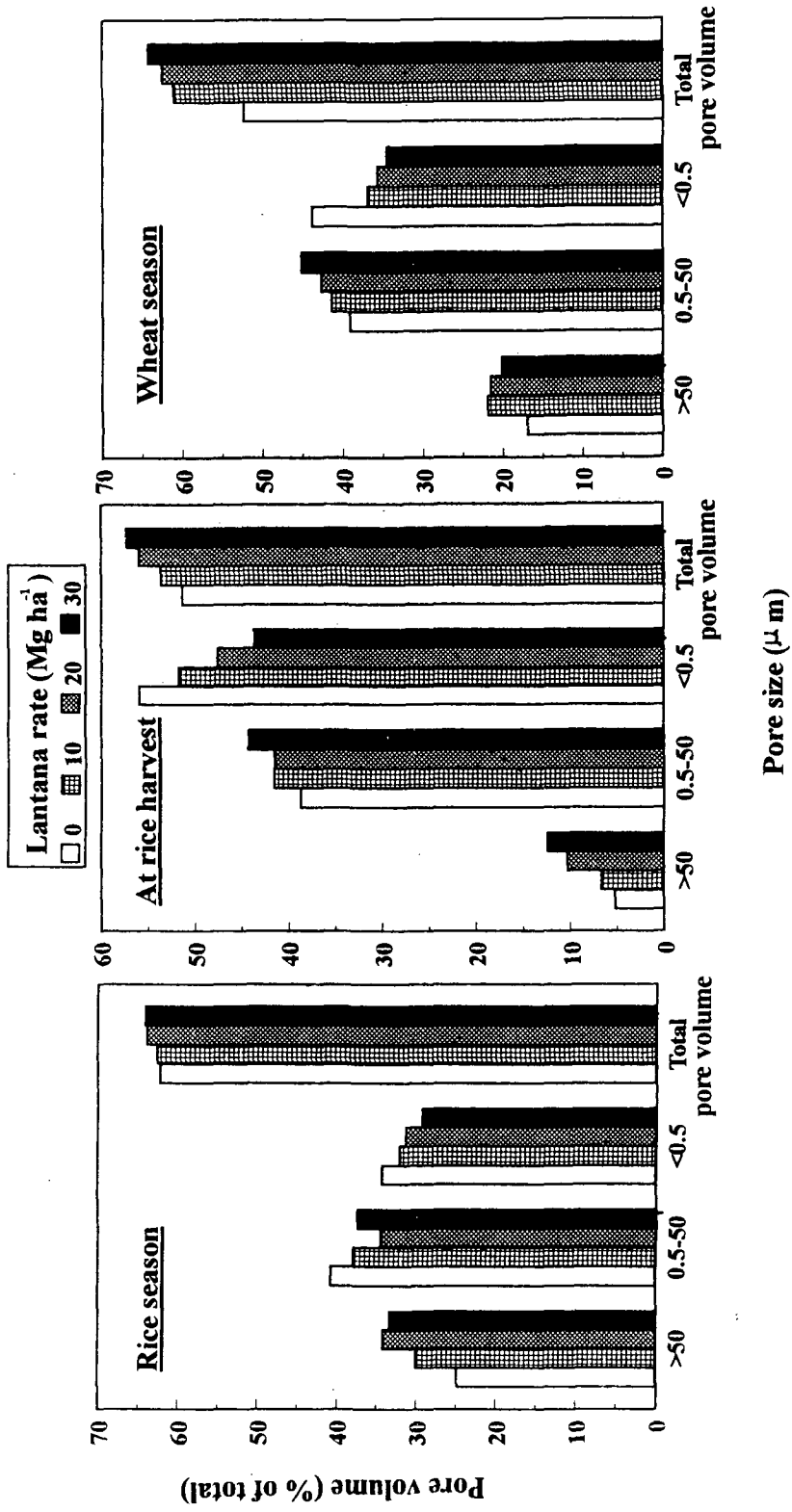


Figure 3. Effect of ten annual applications of lantana biomass on pore-size distribution in 0.075 m soil layer

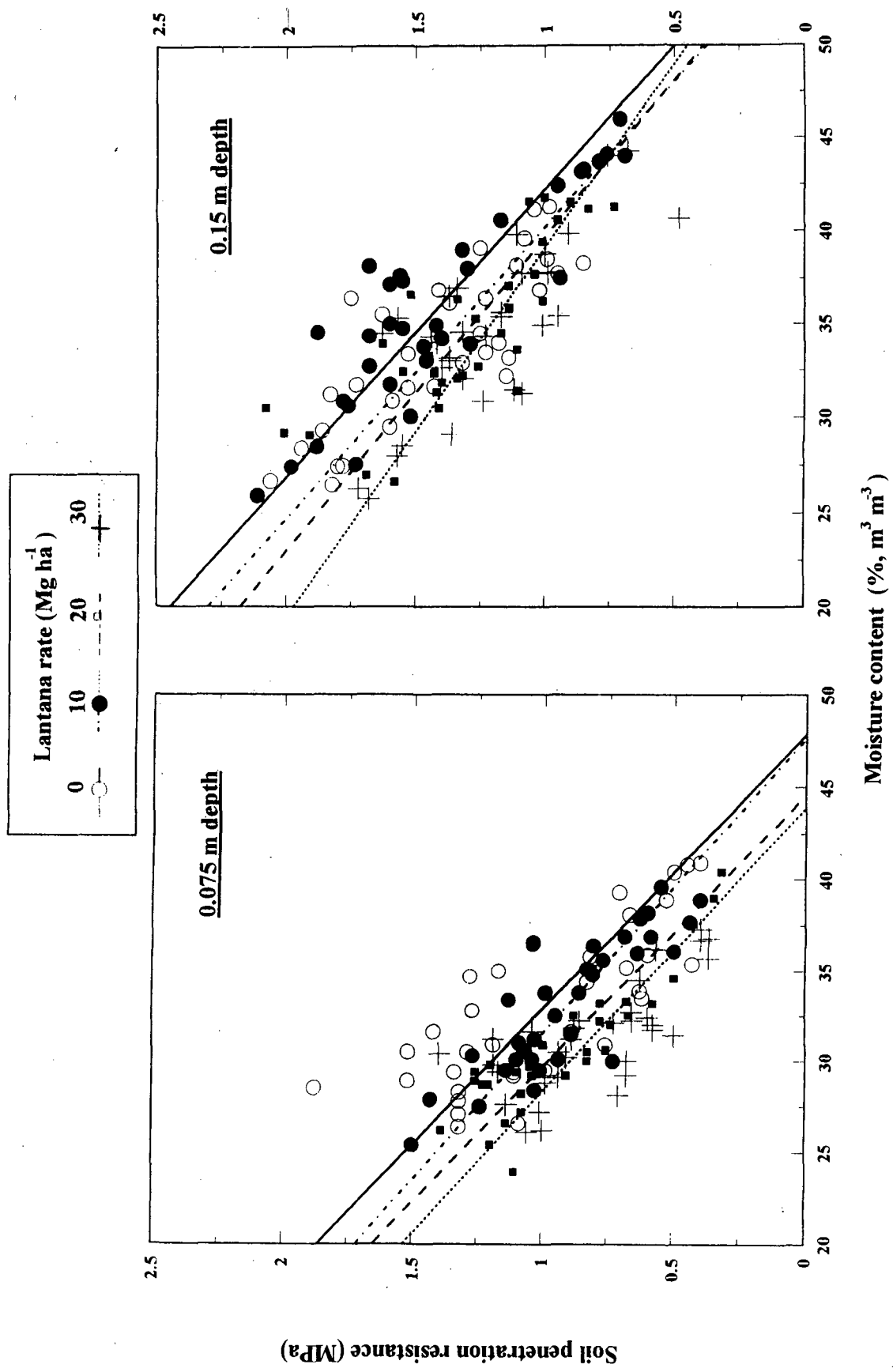


Figure 4. Effect of ten annual applications of lantana biomass on soil penetration resistance at 0.075 and 0.15 m depths during wheat cropping season (at 30 DAS onwards)

At 0.15 m soil depth : (n = 33, 26.0 ≤ θ ≤ 46.0)

$$\text{SPR (M}_0\text{)} = 3.74 - 0.065 \theta; \quad r = -0.887^{**} \quad (4.5)$$

$$\text{SPR (M}_1\text{)} = 3.65 - 0.067 \theta; \quad r = -0.833^{**} \quad (4.6)$$

$$\text{SPR (M}_2\text{)} = 3.37 - 0.060 \theta; \quad r = -0.794^{**} \quad (4.7)$$

$$\text{SPR (M}_3\text{)} = 3.01 - 0.052 \theta; \quad r = -0.793^{**} \quad (4.8)$$

**4.2.3.6 Apparent specific volume :** The apparent specific volume (ASV) determined, both, before and 3-d after puddling, and hence the change in ASV ( $\Delta$  ASV) was significantly ( $P = 0.05$ ) affected by the lantana treatments (Table 8). The ASV was always lowest in control plots and it increased progressively with the increase in amount of lantana added. The differences in ASV values due to lantana additions were non-significant at rates between 10 and 20 Mg ha<sup>-1</sup>, but significant between 20 and 30 Mg ha<sup>-1</sup>. Similar trend was observed in case of  $\Delta$  ASV. The  $\Delta$  ASV increased by 67, 66 and 87 per cent over control with 10, 20 and 30 Mg ha<sup>-1</sup> lantana, respectively.

Table 8 Effect of ten annual applications of lantana biomass on apparent specific volume, change in apparent specific volume ( $\Delta$  ASV), puddling index (PI) and coefficient of linear extensibility (COLE)

Treatment (Lantana, Mg ha <sup>-1</sup> )	Apparent specific volume(cm <sup>3</sup> g <sup>-1</sup> )		$\Delta$ ASV (cm <sup>3</sup> g <sup>-1</sup> )	PI (%)	COLE (cm cm <sup>-1</sup> )
	Before puddling	After puddling			
0	0.675	0.915	0.240	76.7	0.070
10	0.693	1.084	0.401	78.8	0.097
20	0.705	1.116	0.411	80.6	0.101
30	0.745	1.192	0.447	84.6	0.116
LSD (P = 0.05)	0.028	0.076	0.029	1.3	0.019

**4.2.3.7 Puddling Index :** Puddling index, which is the ratio of soil suspension after and before settling for 24 h, increased significantly with the addition of lantana (Table 8). The values of puddling index increased by 3, 5 and 10 per cent over control value of 76.7 per cent. The differences in puddling index were significant at each level of treatment.

**4.2.3.8. Coefficient of Linear Extensibility :** The coefficient of linear extensibility (COLE) increased significantly with the use of lantana as compared to control, although differences in COLE among three lantana rates were non-significant (Table 8). The COLE values increased from 0.070 cm cm<sup>-1</sup> in control to 0.097, 0.101 and 0.116 cm cm<sup>-1</sup> with 10, 20 and 30 Mg ha<sup>-1</sup> lantana, respectively.

**4.2.3.9 Soil Cracking :** Hair-line cracks started appearing at soil surface at 33.7, 39.9, 42.5 and 44.1 per cent moisture content in 0-0.15 m soil layer of the plots treated with 0, 10, 20 and 30 Mg lantana ha<sup>-1</sup>, respectively. The differences in moisture content at which surface soil started cracking were statistically significant (LSD<sub>0.05</sub> = 1.6). The matric suction values at the corresponding moisture contents were 11.3, 9.2, 8.7 and 8.6 kPa, respectively.

Addition of lantana modified the surface cracking pattern of soil. The cracks developed in control plots were wider and deeper than in lantana-treated plots, and almost in an hexagonal pattern. The cracking pattern changed to close-spaced network of fine cracks in lantana treated plots (Plate 1).

Addition of lantana increased the fine cracks (< 5 mm wide) at the expense of wider cracks (>10 mm); cracks of 5-10 mm dia remained almost unchanged (Fig 5). The total length of cracks of sizes < 5, 5-10, 10-15, 15-20 and >20 mm was 176, 289, 180, 149 and 46 m m<sup>-2</sup> in M<sub>0</sub> (control); 458, 280, 123, 65 and 18 m m<sup>-2</sup> in M<sub>1</sub> (10 Mg ha<sup>-1</sup>, lantana); 1050, 354, 67, 13

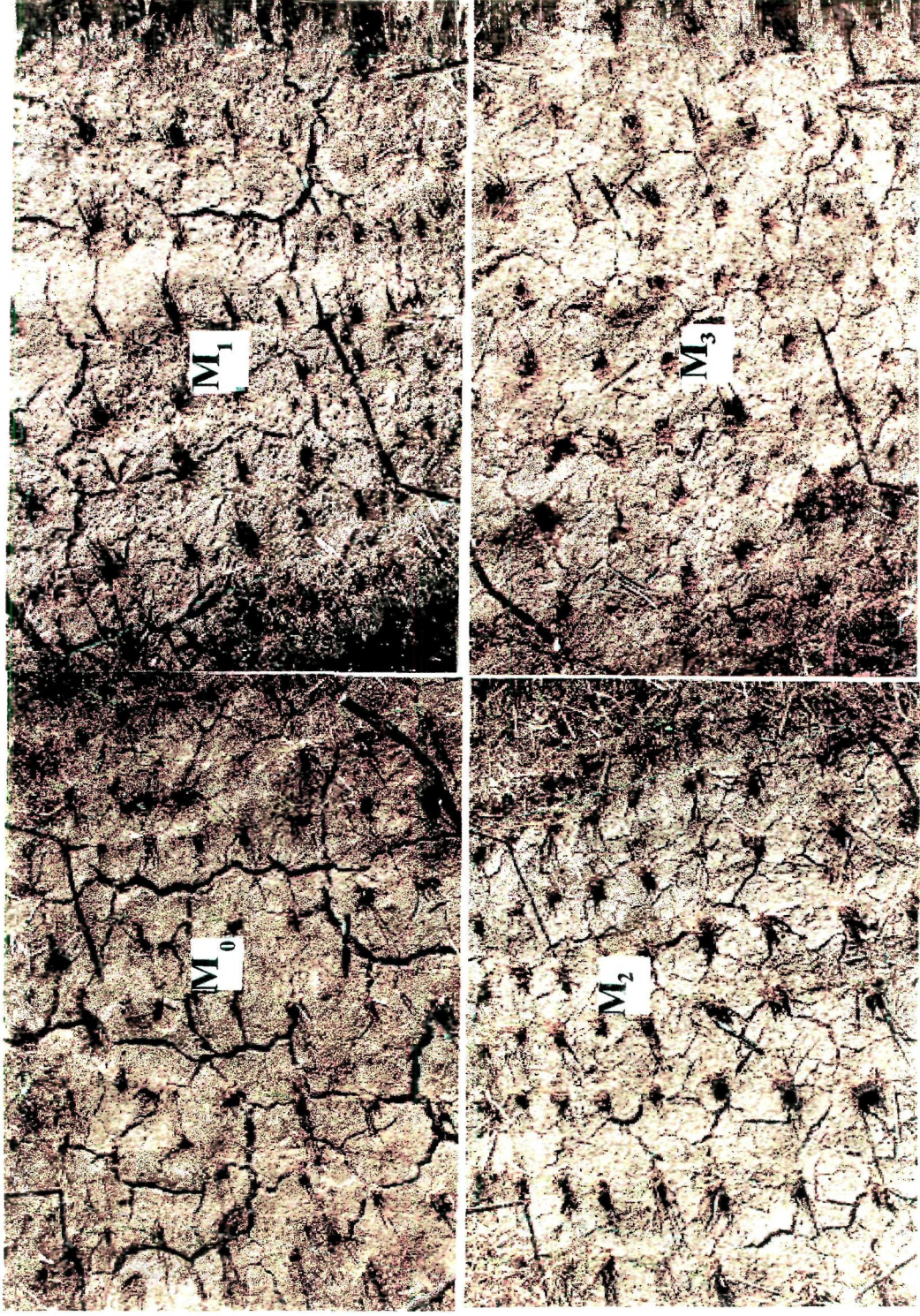


Plate 1. Effect of lantana additions on cracking pattern of rice soil (  $M_0$  no lantana,  $M_1$   $10 \text{ Mg ha}^{-1}$ ,  $M_2$   $20 \text{ Mg ha}^{-1}$ ,  $M_3$   $30 \text{ Mg ha}^{-1}$  lantana)

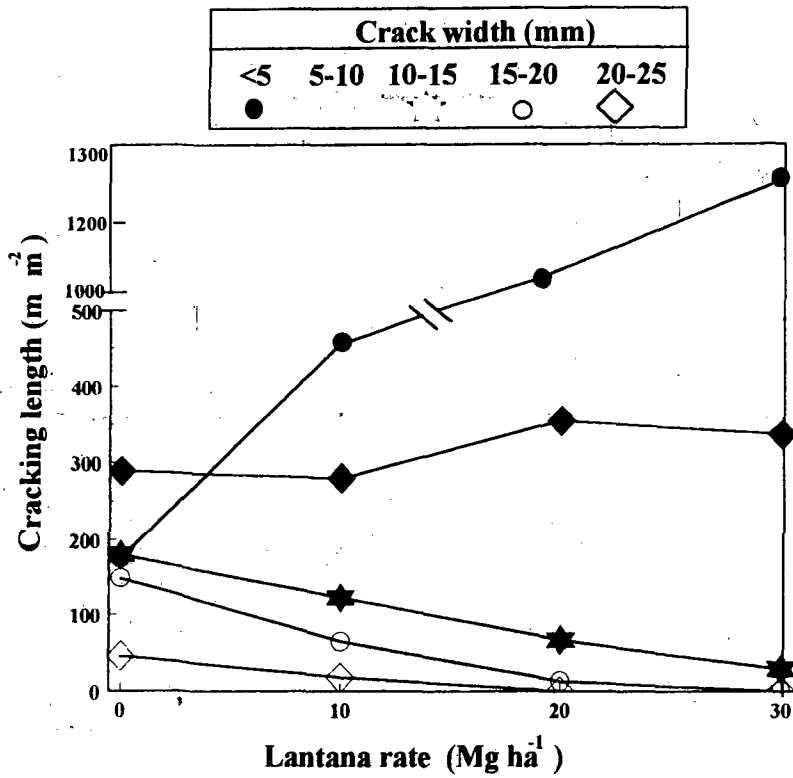


Figure 5. Effect of ten annual additions of lantana biomass on length of cracks in surface soil layer at rice harvest

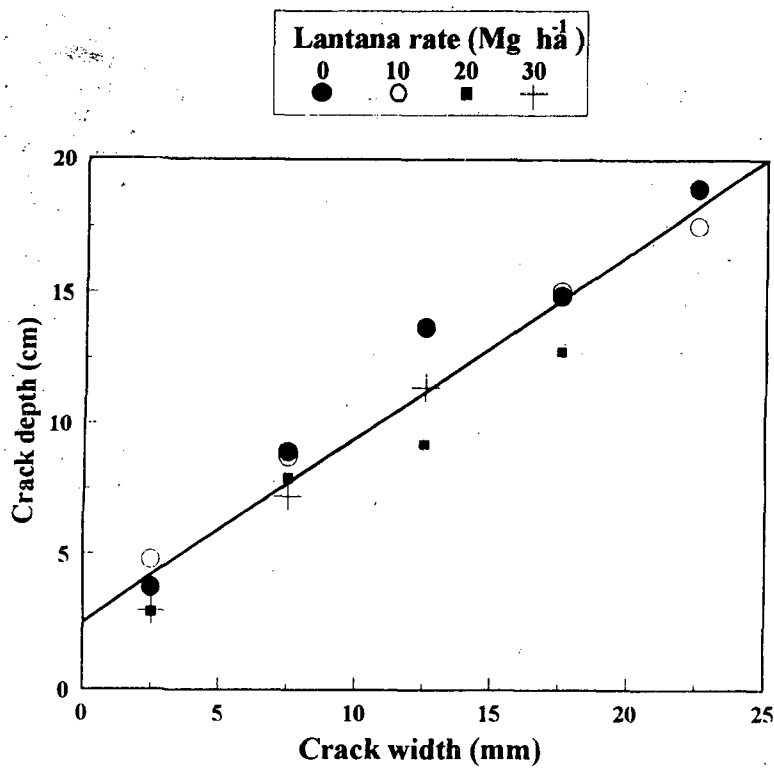


Figure 6. Relationship between width and depth of cracks in surface soil layer at rice harvest

and  $0 \text{ m m}^{-2}$  in  $M_2$  ( $20 \text{ Mg ha}^{-1}$ , lantana); and 1266, 336, 29, 0 and  $0 \text{ m m}^{-2}$  in  $M_3$  ( $30 \text{ Mg ha}^{-1}$ , lantana), respectively.

The crack depth (d,cm) was linearly, positively and significantly correlated with crack width ( $\bar{w}$ , mm) (Eqn. 4.9, Fig.6) as follows : ( $n = 17, 4.78 \leq \bar{w} \leq 19.80$ )

$$d = 2.35 + 0.72 \bar{w}; \quad r = 0.965^{**} \quad (4.9)$$

According to these data average depth of cracks for different width-ranges also decreased with lantana rates. The average depth for width-ranges <5, 5-10, 10-15, 15-20 and >20 mm was 4.8, 8.7, 13.7, 15.1 and 18.9 cm in  $M_0$ ; 3.7, 8.9, 13.7, 14.9 and 17.5 cm in  $M_1$ ; 2.9, 7.2, 9.2, 12.8 and 0.0 in  $M_2$ ; and 2.9, 7.2, 11.4, 0.0 and 0.0 cm in  $M_3$ , respectively. Because of changes in length and depth of cracks of different size-ranges, the volume and surface area of cracks also changed significantly with the lantana treatments (Fig 7). Both of these parameters followed the same trend as the length of cracks. The total volume of the cracks per unit surface area was  $5.30 \times 10^{-4}$ ,  $3.40 \times 10^{-4}$ ,  $1.84 \times 10^{-4}$  and  $1.30 \times 10^{-4} \text{ m}^3 \text{ m}^{-2}$ , and surface area was 1.78, 1.44, 1.17 and  $1.13 \text{ m}^2 \text{ m}^{-2}$  with 0, 10, 20 and  $30 \text{ Mg ha}^{-1}$  lantana, respectively (Fig 8). Thus, the addition of lantana @ 10, 20 and  $30 \text{ Mg ha}^{-1}$  decreased the total volume of cracks by 36, 65 and 76 per cent, and surface area by 19, 34 and 37 per cent over the control, respectively.

**4.2.3.10 Clod-Size Distribution :** The clod-size distribution determined after the land was prepared for wheat sowing after rice harvest is shown in (Table 9). Lantana treatments significantly affected clod-size distribution. The clods of size < 2 cm dia were significantly increased with the lantana treatment from 46.5 per cent in control to 54.7, 56.1 and 61.6 per cent in plots treated with lantana @ 10, 20 and  $30 \text{ Mg ha}^{-1}$ , respectively. The increase was in line with the increase in the rate of lantana application. The clods of the sizes 2-4 cm dia and 4-

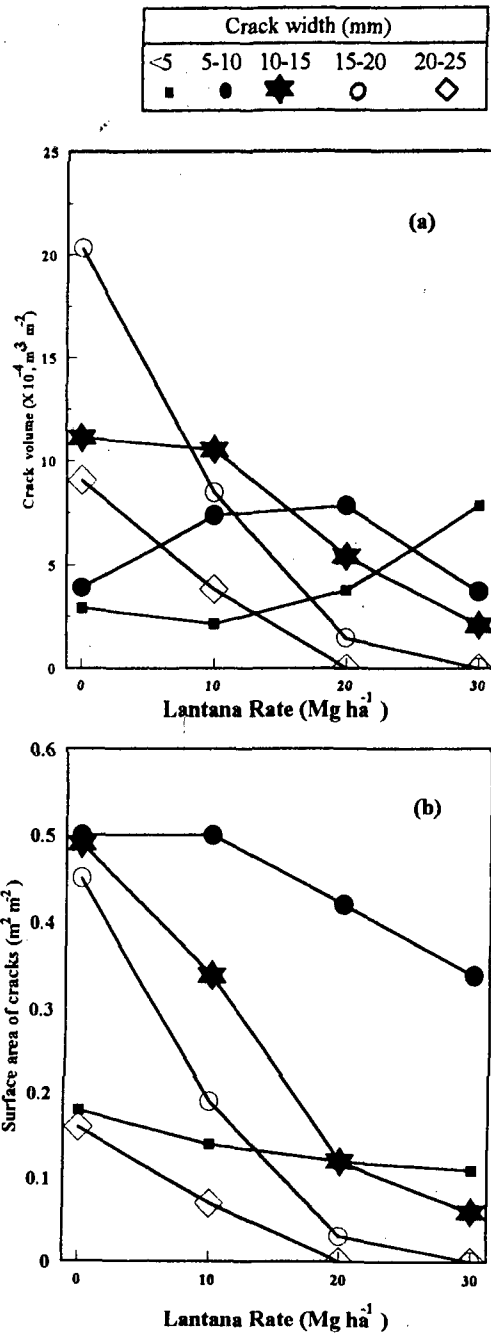


Figure 7. Effect of ten annual applications of lantana biomass on (a) volume and (b) surface area of cracks of different size-ranges

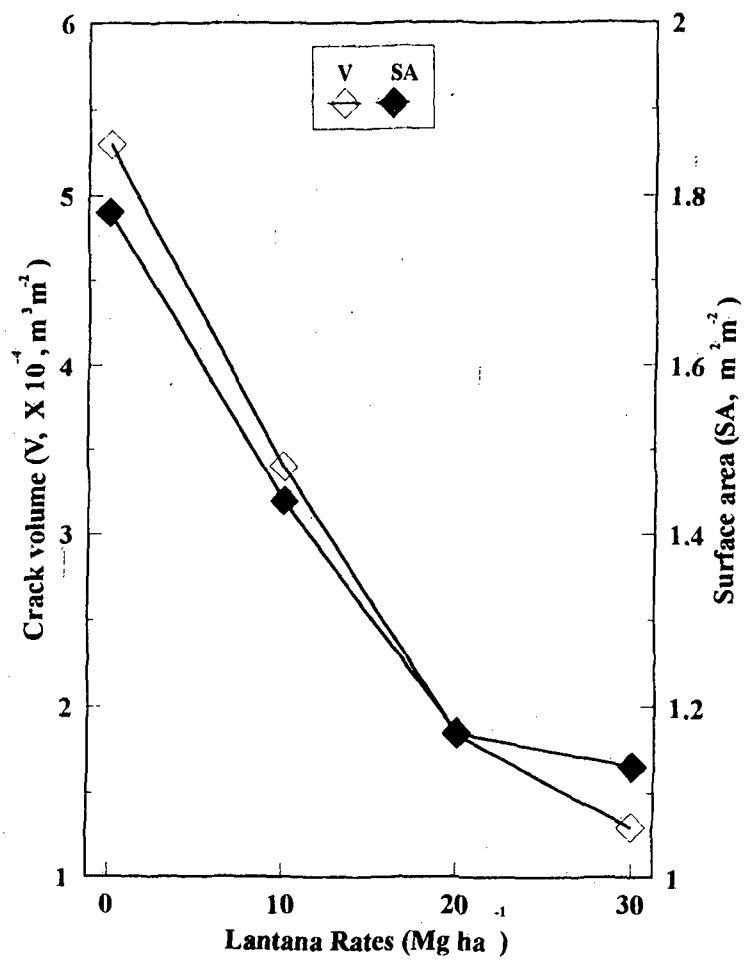


Figure 8. Effect of ten annual applications of lantana on total volume and surface area of cracks

6 cm dia, on the other hand, were highest in control and decreased progressively with the addition of lantana; the differences among different treatments were statistically ( $P = 0.05$ ) significant. The clods of size  $>6$  cm dia were found only in control plots.

Table 9 Effect of ten annual applications of lantana biomass on clod-size distribution in wheat seed bed

Treatment (Lantana rate (Mg ha <sup>-1</sup> ))	Clod-size distribution ( per cent)			
	<2 cm	2-4 cm	4-6 cm	>6 cm
0	46.3	23.7	22.1	7.9
10	54.7	23.8	21.5	nil
20	56.2	22.5	21.3	nil
30	61.3	20.2	18.5	nil
LSD ( $P = 0.05$ )	2.8	2.0	2.4	–

#### 4.2.4 Hydraulic Properties :

**4.2.4.1 Soil-water Retention and Water Availability :** Soil-water retention, expressed on mass-basis and volume-basis, during rice crop (30 DAT), at rice harvest and during wheat crop (30 DAS) are shown in Fig 9 and 10. (Appendix V). The water retention on mass-basis increased with the use of lantana at all the suction values from saturation to permanent wilting point (1500 kPa) in all the treatments and at all the stages (Fig. 9). The increase was more at lower suction values as compared to higher suction values.

When expressed on volume-basis (Fig 10), the increase in water retention was observed at suction values  $< 6$  kPa during rice cropping,  $< 10$  kPa at rice harvest and  $< 50$  kPa during wheat cropping season. At higher suction values, water retention was always lower in lantana-treated than in control plots.

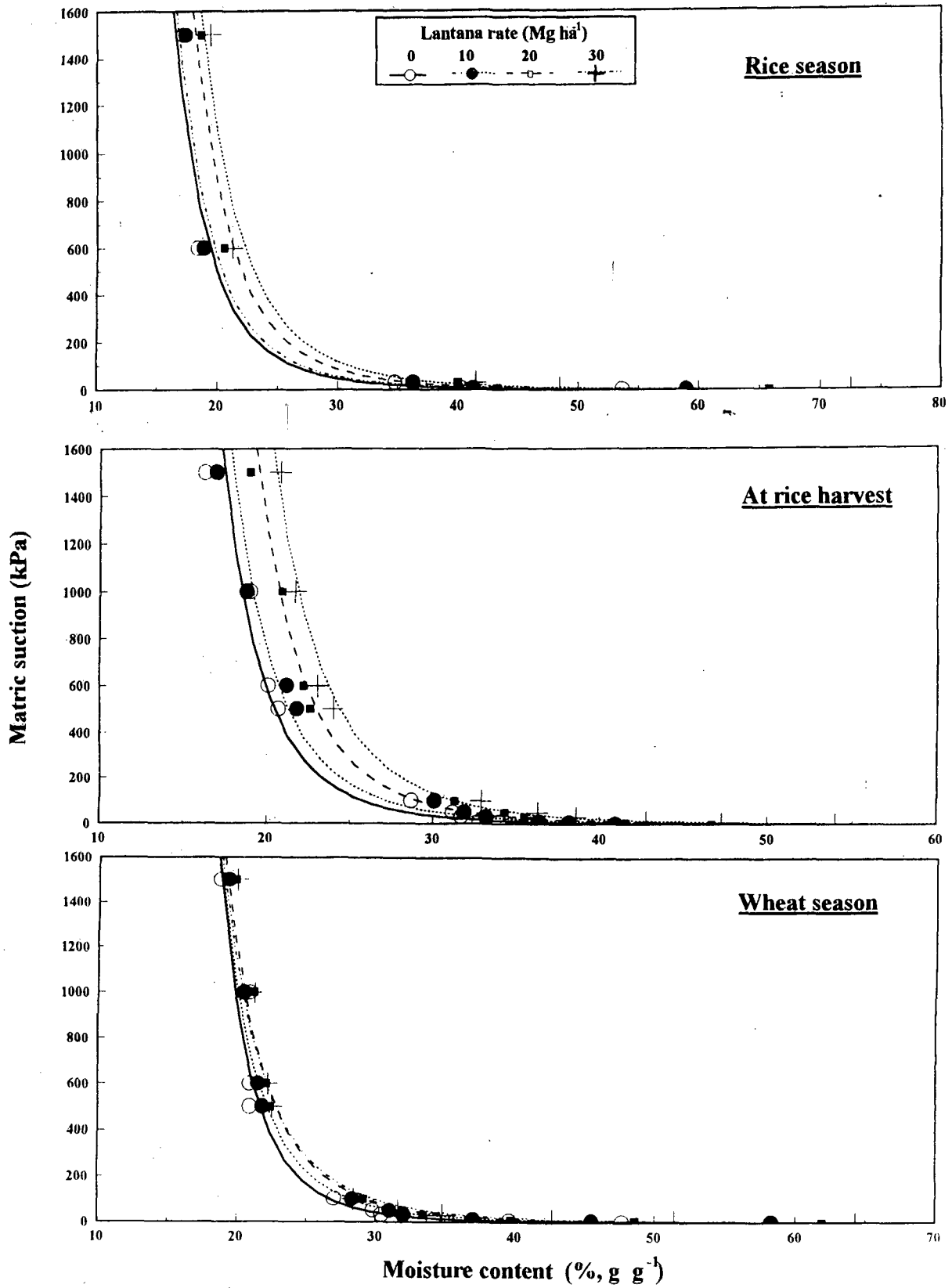


Figure 9. Effect of ten annual applications of lantana biomass on the soil-water retentive (mass-basis) in the top 0.075 m soil layer

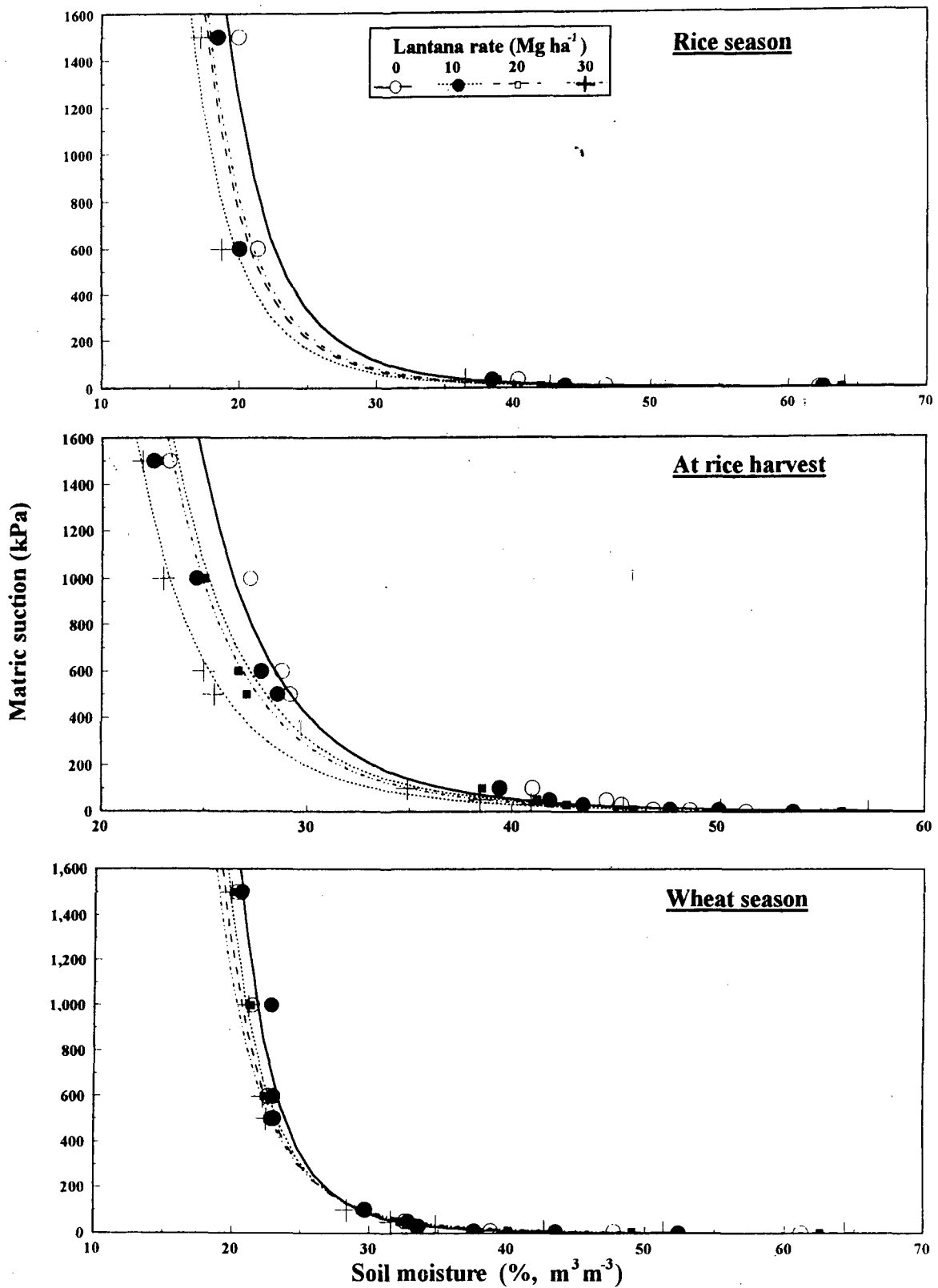


Figure 10. Effect of ten annual additions of lantana biomass on soil moisture retention (volume-basis) in the top 0.075 m soil layer

The plant-available water capacity (PAWC), when expressed on mass-basis increased significantly with lantana additions at all the stages, i.e. during rice cropping, at rice harvest and during wheat season (Table 10). During rice season, the PAWC increased from 17.6 per cent in control to 18.9, 21.4 and 21.9 per cent with 10, 20 and 30 Mg lantana ha<sup>-1</sup>, respectively. The corresponding values at rice harvest were 15.4, 16.0, 18.5 and 17.8 per cent, and during wheat season were 11.7, 12.7, 13.6 and 15.0 per cent, respectively.

On the other hand, when PAWC was expressed on volume-basis (bulk density values given in Table 10), the trend was reversed during and at rice harvest, but did not change during wheat season. The PAWC on volume-basis were statistically same in all plots during rice season, but decreased significantly at rice harvest, from 22.0 per cent in control to 20.9, 19.8 and 18.8 per cent in plots treated with 10, 20 and 30 Mg ha<sup>-1</sup>, respectively. The PAWC during wheat season increased from 12.9 per cent in control to 13.4, 13.7 and 15.0 per cent with three lantana treatments, significantly.

Table 10 Effect of ten annual applications of lantana biomass on plant-available water capacity

Treatment (Lantana, Mg ha <sup>-1</sup> )	Plant Available Water Capacity (per cent)					
	Rice Season		At Rice Harvest		Wheat Season	
	Mass-basis	Vol.-basis	Mass-basis	Vol.-basis	Mass-basis	Vol.-basis
0	17.6	20.4 (1.06)	15.4	22.0 (1.43)	11.7	12.9 (1.10)
10	18.9	20.0 (1.06)	16.0	20.9 (1.31)	12.7	13.4 (1.05)
20	21.4	20.7 (0.97)	16.5	19.8 (1.20)	13.6	13.7 (1.01)
30	21.9	19.0 (0.88)	17.8	18.8 (1.06)	15.0	15.0 (1.00)
LSD (P = 0.05)	0.8	ns	0.7	0.6	1.2	0.9

Note: Values in paranthesis indicate bulk density (Mg m<sup>-3</sup>) in soil.

**4.2.4.2 Infiltration :** Infiltration characteristics of soil treated with lantana and determined at rice and wheat harvest are shown in Fig. 11 and 12 (appendix VI). The infiltration rates at any given time was lowest in control followed by in plots treated with 10, 20 and 30 Mg lantana ha<sup>-1</sup>, respectively. The final infiltrability at rice harvest was  $0.28 \times 10^{-6}$ ,  $0.44 \times 10^{-6}$ ,  $1.12 \times 10^{-6}$  and  $2.22 \times 10^{-6}$  m s<sup>-1</sup> in control and 10, 20 and 30 Mg ha<sup>-1</sup> lantana-treated plots, respectively (Table 11). Thus, the final infiltrability with 10, 20 and 30 Mg ha<sup>-1</sup> lantana at rice harvest was 1.5, 4 and 8 times that of control. The final infiltrability arrived within about 6 hours. The cumulative infiltration during 6 h-period was 0.14, 0.24, 0.44 and 0.67 m with 0, 10, 20 and 30 Mg ha<sup>-1</sup> lantana, respectively.

Similar trends of infiltration were observed after wheat harvest, although the values were substantially higher. The final infiltrability with 10, 20 and 30 Mg lantana ha<sup>-1</sup> was  $17.2 \times 10^{-6}$ ,  $29.6 \times 10^{-6}$  and  $35.5 \times 10^{-6}$  m s<sup>-1</sup> as compared to  $8.7 \times 10^{-6}$  m s<sup>-1</sup> in control (Table 11). Thus, the final infiltrability corresponding to three rates of lantana increased by 2, 3 and 4 times that of control. The final infiltrability was reached in about 10 h-period. The cumulative infiltration values after 10 h were 0.27, 0.63, 2.12 and 2.13 m with 0, 10, 20 and 30 Mg lantana ha<sup>-1</sup>, respectively.

**4.2.4.3 Saturated Hydraulic Conductivity :** The values of saturated hydraulic conductivity (Ks) determined at rice and wheat harvest are shown in Table 11. The Ks at rice harvest increased from  $3.61 \times 10^{-6}$  m s<sup>-1</sup> in control to  $4.61 \times 10^{-6}$ ,  $6.56 \times 10^{-6}$  and  $7.44 \times 10^{-6}$  m s<sup>-1</sup> with 10, 20 and 30 Mg lantana ha<sup>-1</sup>, respectively. The increase was about 1.3, 1.8 and 2.1 times that of Ks in control, respectively. Similarly Ks at wheat harvest was  $16.92 \times 10^{-6}$ ,  $24.19 \times$

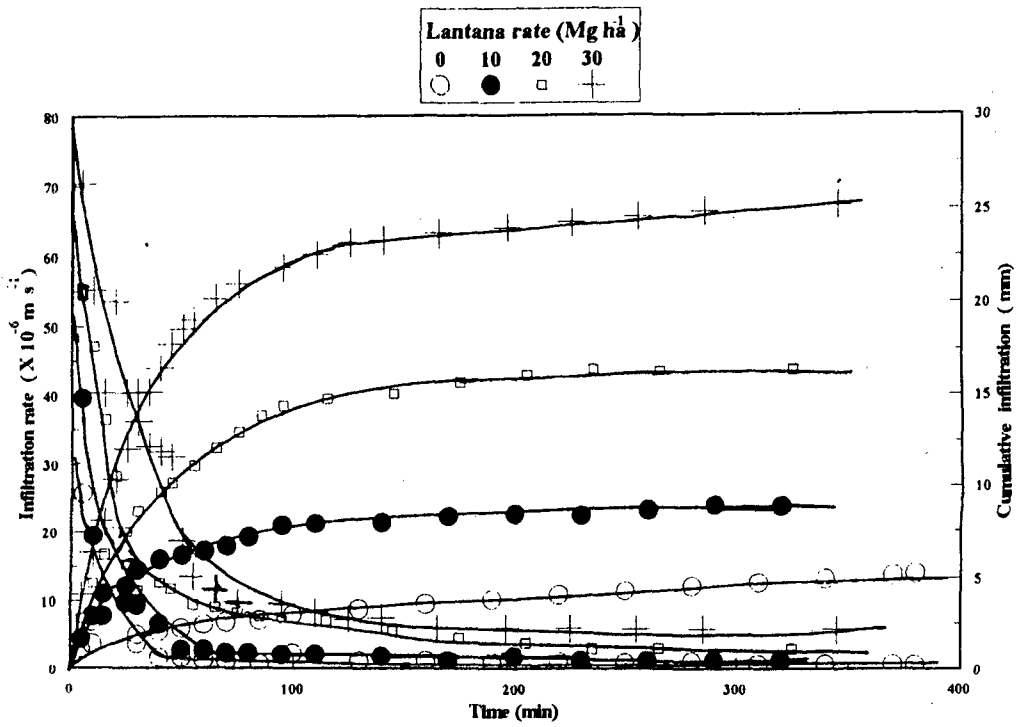


Figure 11. Effect of ten annual applications of lantana biomass on infiltration characteristics of soil at rice harvest

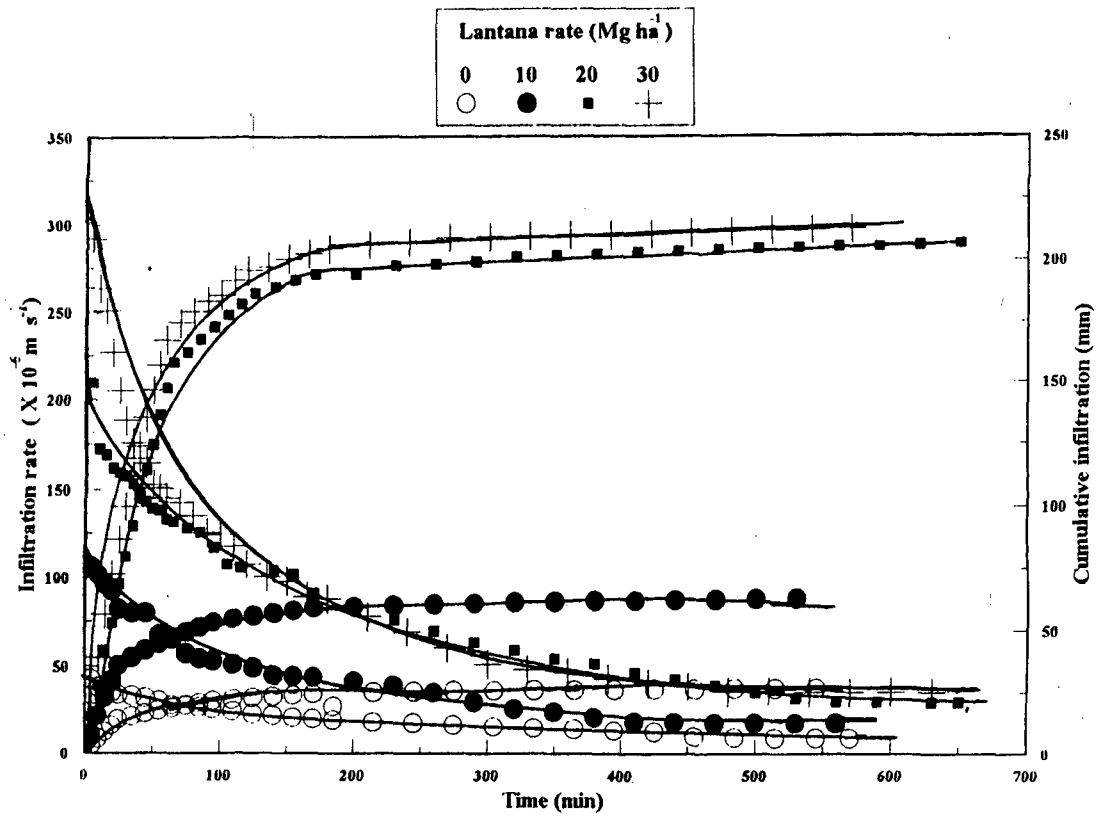


Figure 12. Effect of ten annual applications of lantana biomass on infiltration characteristics of soil at wheat harvest

Table 11 Effect of ten annual applications of lantana biomass on infiltration rate, cumulative infiltration and saturated hydraulic conductivity at rice and wheat harvest

Treatment (Lantana, Mg ha <sup>-1</sup> )	Infiltration Rate ( $\times 10^{-6}$ m s <sup>-1</sup> )		Cumulative Infiltration (m)		Saturated Hydraulic Conductivity* ( $\times 10^{-6}$ m s <sup>-1</sup> )	
	At rice harvest	at wheat harvest	At rice harvest	at wheat harvest	At rice harvest	at wheat harvest
0	0.28	8.7	0.14	0.27	3.61	16.92
10	0.44	17.2	0.24	0.63	4.61	24.19
20	1.12	29.6	0.44	2.12	6.56	37.22
30	2.22	35.5	0.67	2.13	7.44	72.61
LSD (p = 0.05)	-	-	-	-	0.64	5.67

\* In 0-0.15 m soil layer

$10^{-6}$ ,  $37.22 \times 10^{-6}$  and  $72.61 \times 10^{-6}$   $\text{m s}^{-1}$  with 10, 20 and 30 Mg lantana  $\text{ha}^{-1}$ . Thus, at wheat harvest, the Ks increased by 1.4, 2.2 and 4.3 times that of control with three rates of lantana, respectively.

**4.2.4.4, Air-filled porosity :** Air-filled porosity of 0.075-0.105 and 0.15-0.18 m soil layers as a function of soil moisture determined after irrigation of wheat (30 DAS) is shown in Fig 13 (Appendix VII). In both the soil layers, air-filled porosity at a given moisture content was lowest in control; it increased progressively with the increase in amount of lantana added to soil. The soil moisture content in 0.075-0.105 m soil layer corresponding to 10 per cent air-filled porosity, aeration critical for most of the upland crops, was 38.4 per cent in control and it increased to 40.0, 54.5 and 55.7 per cent in the plots treated with 10, 20 and 30 Mg lantana  $\text{ha}^{-1}$ , respectively. The corresponding values of moisture content in 0.15-0.18 m soil layer were 31.4, 32.2, 33.9 and 34.6 per cent, respectively.

Air-filled porosity in 0.075-0.105 and 0.15-0.18 m soil layers as a function of time after irrigation to wheat is shown in Fig 14 (Appendix VII). In 0.15-0.18 m soil layer, the 10 per cent air-filled porosity reached after 22, 15, 12 and 12 days of irrigation in plots treated with 0, 10, 20 and 30 Mg lantana  $\text{ha}^{-1}$ , respectively; while in 0.075-0.105 m soil layer, the 10 per cent air-filled porosity was attained within a few hours after irrigation in lantana treated plots as against 4 days in control plots.

**4.2.4.5 Drying Pattern :** Matric suction values at 0.15 and 0.30 m soil depths as a function of time after the plots received the last irrigation on 89 DAT are shown in Fig. 15 (Appendix VIII). The matric suction at 0.15 m soil depth increased gradually and at almost the same rate in all plots upto 110 DAT (the rice crop was harvested at 114 DAT), after which the increase in matric suction was relatively higher in control than in lantana-treated

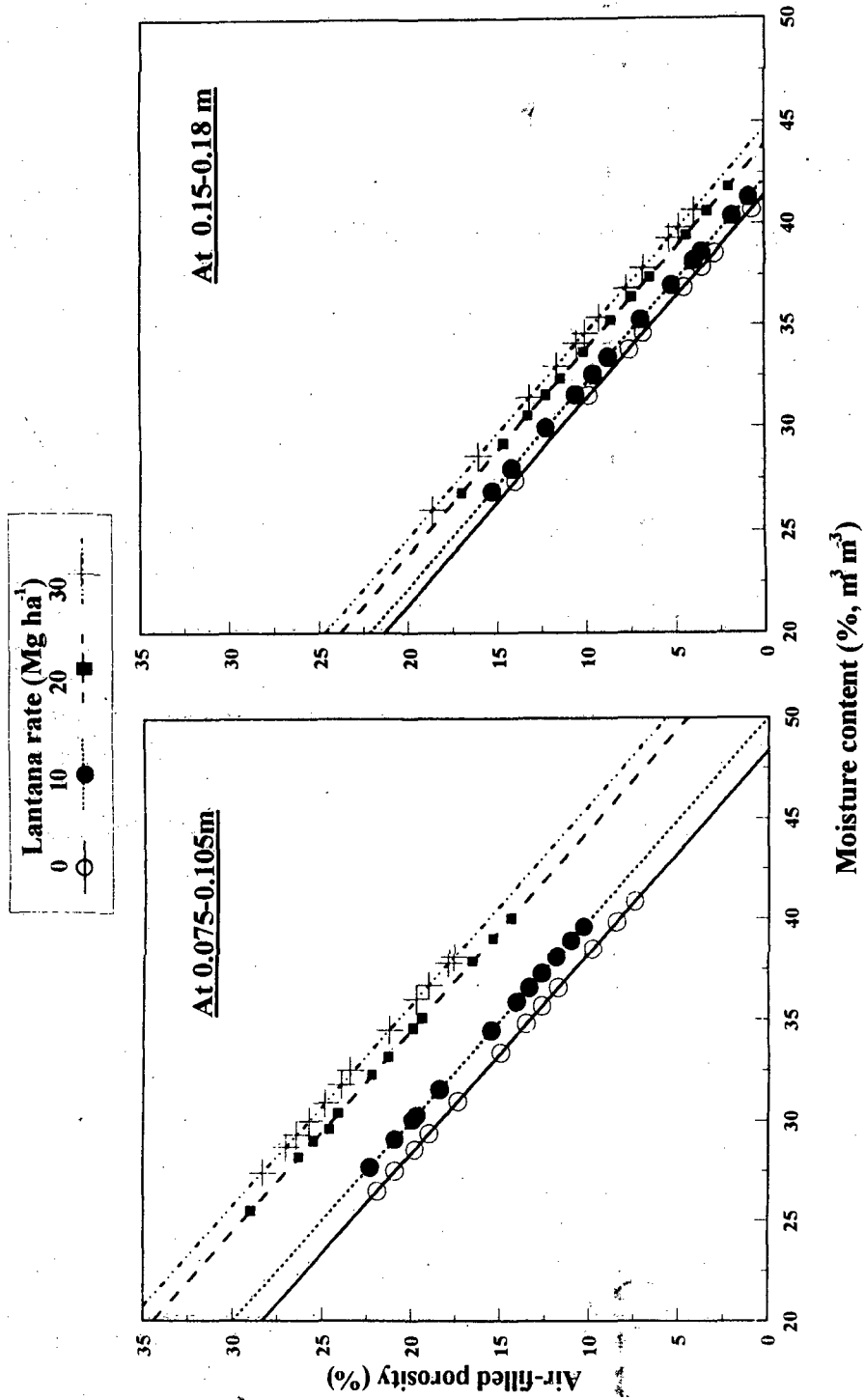


Figure 13. Effect of ten annual applications of lantana biomass on air-filled porosity in relation to moisture content during wheat cropping season (at 30 DAS onwards)

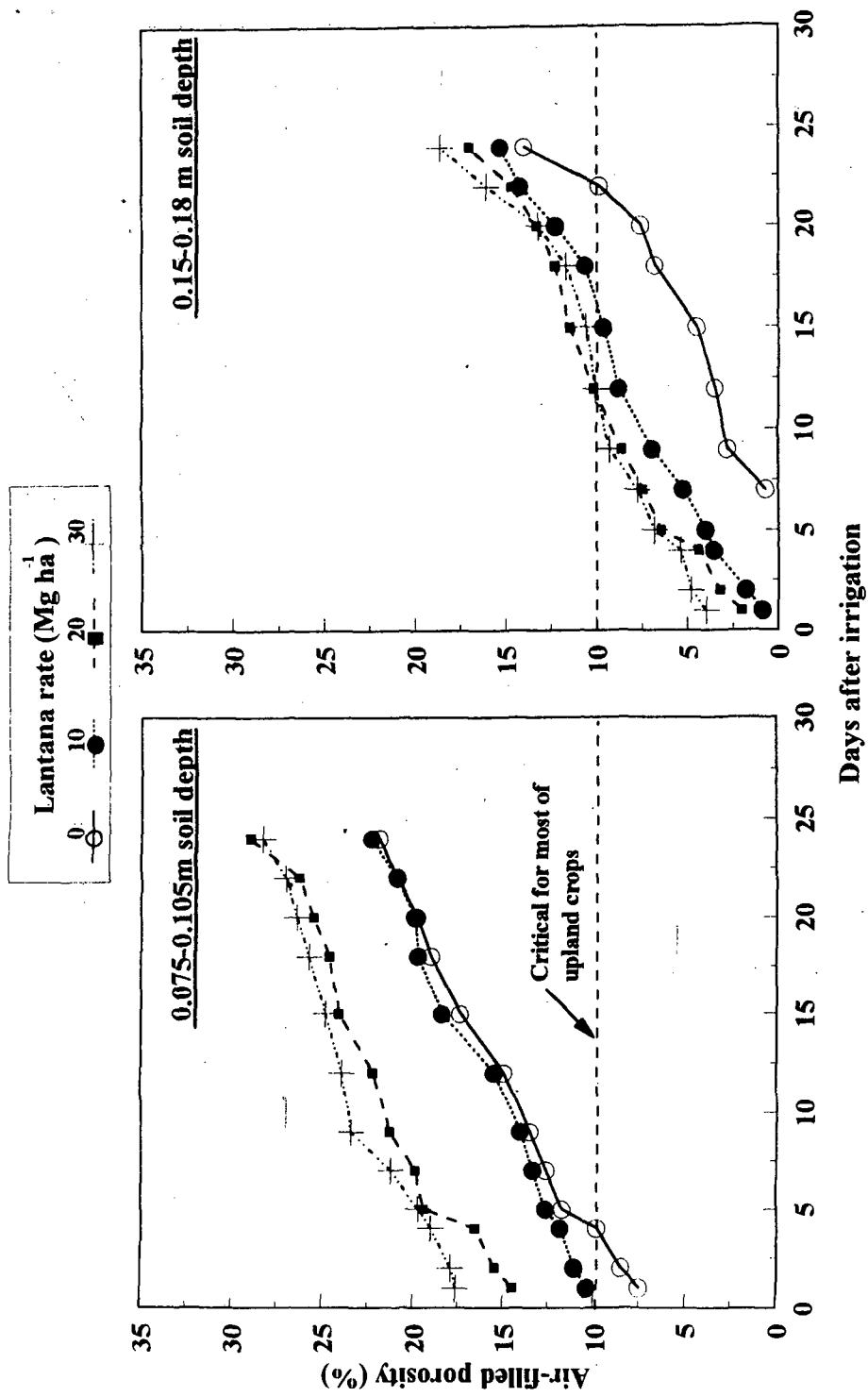


Figure 14. Effect of ten annual applications on lantana biomass on the changes in air-filled capacity with time during wheat cropping season (at 30 DAS onwards)

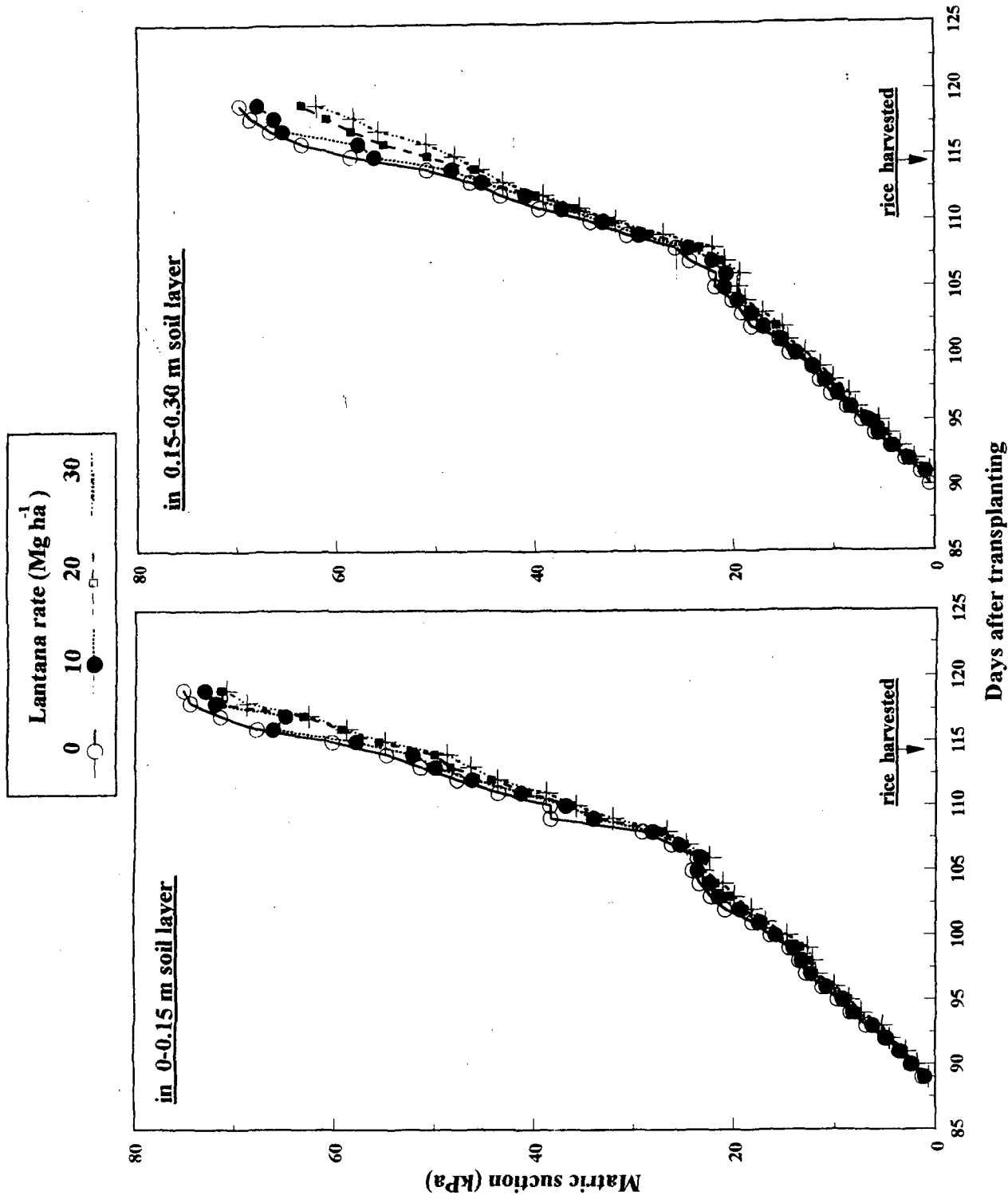


Figure 15. Effect of ten annual applications of lantana biomass on the matric suction of surface and subsurface layers

4.2.4.6 plots. Thus, after 110 DAT matric suction at any time followed the trend of  $M_0 > M_1 > M_2 > M_3$ , although the differences in matric suction among different treatments were not very large.

The matric suction ( $\psi_m$ , kPa) increased as a power function of time (t, days after last irrigation to rice) in both the layers. The regression equation is as follows :

0-0.15 m soil layer (n = 31;  $1 \leq t \leq 31$ )

$$\psi_m(M_0) = 0.96 t^{1.20}, \quad r = 0.988^{**} \quad (4.10)$$

$$\psi_m(M_1) = 0.87 t^{1.22}, \quad r = 0.991^{**} \quad (4.11)$$

$$\psi_m(M_2) = 0.79 t^{1.25}, \quad r = 0.992^{**} \quad (4.12)$$

$$\psi_m(M_3) = 0.66 t^{1.30}, \quad r = 0.994^{**} \quad (4.13)$$

0.15-0.30 m soil layer (n = 29;  $1 \leq t \leq 29$ )

$$\psi_m(M_0) = 0.31 t^{1.54}, \quad r = 0.992^{**} \quad (4.14)$$

$$\psi_m(M_1) = 0.25 t^{1.60}, \quad r = 0.989^{**} \quad (4.15)$$

$$\psi_m(M_2) = 0.23 t^{1.63}, \quad r = 0.989^{**} \quad (4.16)$$

$$\psi_m(M_3) = 0.18 t^{1.70}, \quad r = 0.985^{**} \quad (4.17)$$

**4.2.4.6 Soil-Water Contact Angle :** The incorporation of lantana for ten years increased the soil-water contact angle. The soil-water contact angle was  $72.0^\circ$  in control, which increased to  $72.7^\circ$ ,  $74.4^\circ$  and  $76.0^\circ$  with lantana @ 10, 20 and 30 Mg ha<sup>-1</sup>, respectively.

## 4.2.5 Mechanical Properties

**4.2.5.1 Soil Consistency limits :** All the soil consistency limits, viz. Liquid limit, plastic limit, plasticity index and shrinkage limit, were affected significantly with the use of lantana (Table 12). The moisture content at liquid limit was increased from 37.5 per cent in control to 39.1, 40.7 and 42.1 per cent with 10, 20 and 30 Mg lantana ha<sup>-1</sup>; the corresponding values of moisture content at plastic limit were 27.2, 28.5, 29.6 and 30.6 per cent,

respectively. The data show that the increase in moisture content at liquid limit was relatively more than at plastic limit. It resulted into significant increase in plasticity index. The values in control and lantana-treated plots @ 10, 20 and 30 Mg ha<sup>-1</sup> were 10.3, 10.5, 11.1 and 11.5 per cent, respectively. According to Attraberg (1913) as quoted by Jumikis (1967), all the soils were in the medium plastic range.

Table 12 Effect of ten annual applications of lantana on soil consistency limits determined at rice harvest

Treatment Lantana, Mg ha <sup>-1</sup> )	Soil Moisture Content (%) at				
	Liquid Limit	Plastic Limit	Plasticity Index	Shrinkage Limit	Friability range
0	37.5	27.2	10.3	18.3	8.9
10	39.1	28.5	10.5	20.3	8.2
20	40.7	29.6	11.1	21.8	7.8
30	42.1	30.6	11.5	22.8	7.8
LSD (P = 0.05)	1.6	1.1	0.5	1.0	0.4

The moisture content at shrinkage limit also increased from 18.3 per cent in control to 20.3, 21.8 and 22.8 per cent in plots treated with lantana @10, 20 and 30 Mg ha<sup>-1</sup>, respectively. The moisture content at friability range decreased significantly from 8.9 per cent (in control) to 8.2, 7.8 and 7.8 per cent in plots treated with 10, 20 and 30 Mg ha<sup>-1</sup> lantana, respectively.

**4.2.5.2 Energy Required for Land Preparation :** The plots were dug and pulverised manually one month after rice harvest for sowing of wheat at an average moisture content of 29.6 (± 2.7) per cent. The energy required to prepare land decreased significantly (Table 13) from 1.9 GJ ha<sup>-1</sup> in control to 1.46, 1.25 and 1.01 GJ ha<sup>-1</sup> in plots treated with 10, 20

and 30 Mg ha<sup>-1</sup> lantana, respectively. Thus, the use of lantana @ 10, 20 and 30 Mg ha<sup>-1</sup> decreased the energy requirement by 23, 34 and 47 per cent over control.

Table 13 Effect of ten annual applications of lantana on energy required for land preparation for sowing of wheat

Treatment (Lantana, Mg ha <sup>-1</sup> )	Energy required for land preparation (GJ ha <sup>-1</sup> )
0	1.90
10	1.46
20	1.25
30	1.01
LSD (P = 0.05)	0.12

**4.2.5.3 Clod Breaking Strength :** The breaking strength of clods of sizes 2-6 cm dia (CBS) determined after tillage for wheat was affected significantly with lantana treatments and moisture content of clods (Fig 16, Appendix IX). The CBS at any moisture content below 25 per cent was highest in control plots and decreased progressively with the increase in amount of lantana added. For example, at 11 per cent moisture content of clods the CBS was 636.7, 450.8, 381.5 and 371.1 kPa in plots treated with lantana @ 0, 10, 20 and 30 Mg ha<sup>-1</sup>, respectively (below moisture content of 11 per cent, it was difficult to break the clods with the clod-breaking apparatus used in this study). The CBS above 25 per cent moisture of clods was almost the same for all the treatments.

The CBS was significantly, negatively and exponentially correlated with moisture content of clods. The following relationships between CBS (kPa) and moisture content of clods ( $w$ , per cent) were observed : ( $n = 12, 10.3 \leq w \leq 25.8$ )

$$\text{CBS (M}_0\text{)} = 8.274 e^{-0.165 w}, \quad r = -0.991^{**} \quad (4.18)$$

$$\text{CBS (M}_1\text{)} = 7.712 e^{-0.145 w}, \quad r = -0.990^{**} \quad (4.19)$$

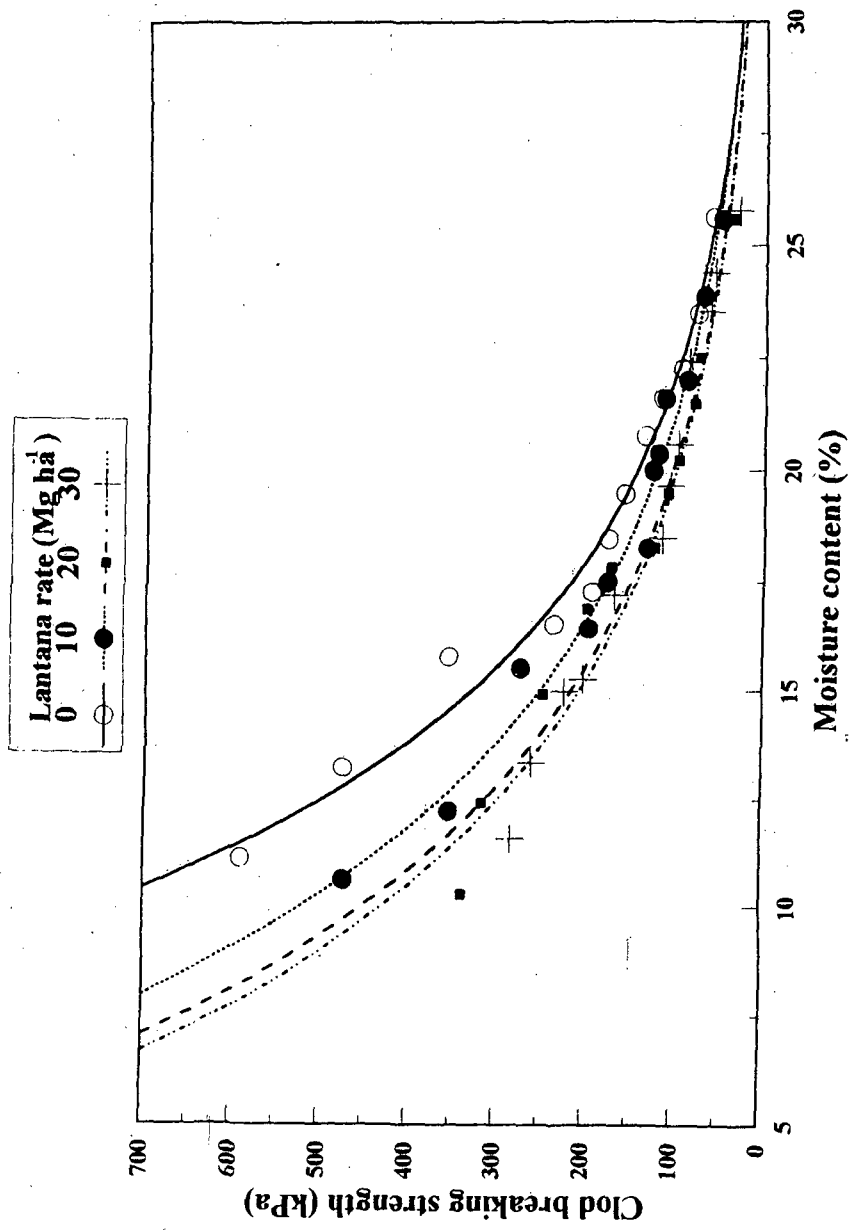


Figure 16. Effect of ten annual applications of lantana biomass on clod breaking strength

$$\text{CBS (M}_2\text{)} = 7.538 e^{-0.145 w}; \quad r = -0.973^{**} \quad (4.20)$$

$$\text{CBS (M}_3\text{)} = 7.518 e^{-0.146 w}; \quad r = -0.976^{**} \quad (4.21)$$

The CBS (kPa) was linearly, positively and significantly correlated with bulk density of clods ( $\rho_b$ ,  $\text{Mg m}^{-3}$ ) ( $n = 4$ ,  $1.49 \geq \rho_b \geq 1.36$ )

$$\text{CBS} = -2251.1 + 1919.4 \rho_b; \quad r = 0.975^* \quad (4.22)$$

### 4.3 Crop Studies

#### 4.3.1 Root Studies

Spatial distribution of wheat roots is shown in Plate 2. The root-spread was wider and deeper in lantana-treated plots than in control plots. The rooting depth was about 0.30 m in control, which increased to 0.35, 0.35 and 0.40 m in plots treated with 10, 20 and 30  $\text{Mg ha}^{-1}$  lantana, respectively.

The root mass density (RMD) at 0-0.15 and 0.15-0.30 m soil depth is shown in Table 14. The RMD increased significantly with increasing levels of lantana and fertilizer levels (NPK), and their interaction effects were also significant.

The RMD at 0-0.15 m soil depth increased from  $1.563 \text{ kg m}^{-3}$  in control ( $M_0$ ) to 1.743, 2.350 and  $2.735 \text{ kg m}^{-3}$  in plots treated with 10 ( $M_1$ ), 20 ( $M_2$ ) and 30 ( $M_3$ )  $\text{Mg ha}^{-1}$  lantana, respectively. The corresponding values at 0.15-0.30 m soil depth were 0.270, 0.296, 0.346 and  $0.427 \text{ kg m}^{-3}$ , respectively. The main effect of fertilizer on RMD was also significant. The RMD values in 0-0.15 m soil layer increased from  $1.826 \text{ kg m}^{-3}$  with  $F_1$  fertilizer treatment (33 per cent NK to rice + 66 per cent NPK to wheat) to 2.093 and  $2.737 \text{ kg m}^{-3}$  with  $F_2$  (66 per cent NK to rice + 66 per cent NPK to wheat) and  $F_3$  (100 per cent NK to rice + 66 per cent NPK to wheat) fertilizer treatments. Similarly the RMD in 0.15-0.30 m soil layer was 0.305, 0.332 and  $0.376 \text{ kg m}^{-3}$ , respectively, with three fertilizer levels.



Plate 2. Effect of lantana on wheat root system ( $M_0$ = no lantana,  $M_1$ = 10 Mg ha<sup>-1</sup>,  $M_2$ = 20 Mg ha<sup>-1</sup>,  $M_3$ = 30 Mg ha<sup>-1</sup> lantana)

Table 14 Effect of ten annual applications of lantana biomass on root mass density of wheat during tenth rice-wheat cropping cycle

Treatment (Lantana Mg ha <sup>-1</sup> )	Root Mass Density (kg m <sup>-3</sup> )									
	0-0.15 m			0.15-0.30 m			Mean			
	F <sub>1</sub>	F <sub>2</sub>	F <sub>3</sub>	F <sub>1</sub>	F <sub>2</sub>	F <sub>3</sub>	F <sub>1</sub>	F <sub>2</sub>	F <sub>3</sub>	Mean
0	1.446	1.446	1.796	0.256	0.264	0.290	0.256	0.264	0.290	0.270
10	1.541	1.802	1.885	0.264	0.297	0.326	0.264	0.297	0.326	0.296
20	1.947	2.347	2.756	0.308	0.344	0.385	0.308	0.344	0.385	0.346
30	2.368	2.777	3.055	0.391	0.421	0.468	0.391	0.421	0.468	0.427
Mean	1.826	2.093	2.737	0.305	0.332	0.367	0.305	0.332	0.367	
LSD (P = 0.05)	Lantana = 0.192	Fertilizer = 0.167	Lantana × fertilizer = 0.350							

Note : F<sub>1</sub> = 33 per cent NK to rice + 66 per cent NPK to wheat

F<sub>2</sub> = 66 per cent NK to rice + 66 per cent NPK to wheat

F<sub>3</sub> = 100 per cent NK to rice + 66 per cent NPK to wheat

The interaction effects of lantana and fertilizer on RMD were also significant at both the soil depths. The RMD in 0-0.15 m soil layer was highest ( $3.055 \text{ kg m}^{-3}$ ) with  $M_3F_3$  treatment. The RMD with  $M_2F_1$  ( $1.947 \text{ kg m}^{-3}$ ) was at par with  $M_0F_3$  ( $1.796 \text{ kg m}^{-3}$ ). The lowest RMD was  $1.446 \text{ kg m}^{-3}$  with  $M_0F_1$  treatment. Similarly in 0.15-0.30 m soil layer RMD was highest ( $0.486 \text{ kg m}^{-3}$ ) with  $M_3F_3$ . The RMD at  $M_3F_1$  ( $0.391 \text{ kg m}^{-3}$ ) was at par with  $M_1F_3$  ( $0.326 \text{ kg m}^{-3}$ ) and RMD at  $M_2F_1$  ( $0.308 \text{ kg m}^{-3}$ ) was at par with  $M_0F_2$  ( $0.264 \text{ kg m}^{-3}$ ) treatment. The RMD was lowest ( $0.256 \text{ kg m}^{-3}$ ) with  $M_0F_1$  treatment.

#### 4.3.2 Shoot/root Ratio :

Shoot/root ratio of wheat is shown in Table 15. The shoot/root ratio was significantly affected by lantana treatments and not by fertilizer treatments; however, the

Table 15 Effect of ten annual applications of lantana on shoot/root ratio of wheat during tenth rice-wheat cropping cycle

Treatment (lantana, $\text{Mg ha}^{-1}$ )	Shoot/root Ratio			
	F <sub>1</sub>	F <sub>2</sub>	F <sub>3</sub>	Mean
0	6.37	6.62	6.62	6.54
10	7.94	8.62	8.77	8.4
20	9.01	9.35	9.43	9.26
30	9.09	10.87	11.90	10.52
Mean	7.94	8.55	8.85	
LSD (P = 0.05)	Lantana	= 1.74		
	Fertilizer	= ns		
	Lantana × fertilizer	= 2.69		

Note : F<sub>1</sub> = 33 % NK to rice + 66 % NPK to wheat  
 F<sub>2</sub> = 66 % NK to rice + 66 % NPK to wheat  
 F<sub>3</sub> = 100 % NK to rice + 66 % NPK to wheat

interaction effects of two were statistically significant. Incorporation of lantana @ 10 ( $M_0$ ), 20 ( $M_1$ ) and 30 ( $M_3$ )  $Mg\ ha^{-1}\ year^{-1}$ , increased the shoot/root ratio from 6.54 in control to 8.40, 9.26 and 10.52, respectively. The interaction effects of lantana and fertilizer showed that lowest shoot/root ratio was 6.37 with  $M_0F_1$  and highest was 11.90 with  $M_3F_3$  treatment.

### 4.3.3 Crop Yields

**4.3.3.1 Rice yield :** Grain yield of rice in 1996 was adversely affected by the severe incidence of blast disease. Hence, in 1996, instead of grain and straw yields, total biomass was recorded. The effects of lantana and fertilizers on rice yield are reported in Table 16. Rice yield was significantly affected by lantana and fertilizer treatments; their interaction effects were also significant.

During 1996, the total biomass production irrespective of fertilizer levels was 9.82  $Mg\ ha^{-1}$  in control ( $M_0$ ) plots and increased significantly to 11.40, 12.56 and 12.98  $Mg\ ha^{-1}$  in plots treated with 10 ( $M_1$ ), 20 ( $M_2$ ) and 30 ( $M_3$ )  $Mg\ ha^{-1}$  lantana, respectively. The total biomass was statistically same at 20 and 30  $Mg\ ha^{-1}$  lantana. Averaging over different lantana levels, the lowest biomass (10.74  $Mg\ ha^{-1}$ ) was produced with 50 per cent of recommended NPK ( $F_1$ ), followed by 11.70 and 12.63  $Mg\ ha^{-1}$  at 75 per cent ( $F_2$ ) and 100 per cent ( $F_3$ ) of recommended NPK fertilizers, respectively, and the differences in biomass production were statistically significant.

The interaction effect of lantana and fertilizers was also significant. The highest biomass production (13.60  $Mg\ ha^{-1}$ ) was obtained with  $M_3F_3$  which was statistically at par with  $M_3F_1$  (12.07  $Mg\ ha^{-1}$ ),  $M_2F_2$  (12.70  $Mg\ ha^{-1}$ ) and  $M_1F_3$  (12.50  $Mg\ ha^{-1}$ ) treatments. The total biomass production was lowest with  $M_0F_1$  (8.80  $Mg\ ha^{-1}$ ) treatment. The

Table 16 Effect of lantana biomass on rice yields during ninth and tenth rice-wheat cropping cycle

Treatment (Lantana, Mg ha <sup>-1</sup> )	Rice Yield (Mg ha <sup>-1</sup> )											
	1996						1997					
	Total Biomass			Grain Yield			Straw Yield			Straw Yield		
	F <sub>1</sub>	F <sub>2</sub>	F <sub>3</sub>	Mean	F <sub>1</sub>	F <sub>2</sub>	F <sub>3</sub>	Mean	F <sub>1</sub>	F <sub>2</sub>	F <sub>3</sub>	Mean
0	8.80	9.73	10.93	9.82	1.77	1.96	2.13	1.95	5.43	6.13	7.85	6.47
10	10.60	11.10	12.50	11.40	2.19	2.40	2.50	2.36	8.47	9.06	9.07	9.10
20	11.50	12.70	13.47	12.56	2.33	2.81	3.29	2.81	9.47	9.24	10.73	10.14
30	12.07	13.27	13.60	12.98	3.48	3.57	3.71	3.58	11.11	11.20	11.16	11.16
Mean	10.47	11.70	12.63	12.63	2.44	2.69	2.91	2.91	8.82	9.16	9.88	9.88
LSD (P = 0.05)	Lantana	= 0.64			= 0.24				= 0.51			
	Fertilizer	= 0.55			= 0.21				= 0.41			
	Lantana × fertilizer	= 0.77			= 0.49				= 0.88			

Note : During 1996:

F<sub>1</sub> = 50 % of recommended NPK to riceF<sub>2</sub> = 75 % of recommended NPK to riceF<sub>3</sub> = 100 % of recommended NPK to rice

During 1997 :

F<sub>1</sub> = 33 % of recommended NK to riceF<sub>2</sub> = 66 % of recommended NK to riceF<sub>3</sub> = 100 % of recommended NK to rice

boimass production with  $M_3F_1$  ( $12.07 \text{ Mg ha}^{-1}$ ) was at par with  $M_0F_3$  ( $10.93 \text{ Mg ha}^{-1}$ ) treatment.

During 1997, the grain and straw yields of rice were significantly affected by all the treatment combinations (Table 16). The grain yield of rice increased significantly from  $1.95 \text{ Mg ha}^{-1}$  in control ( $M_0$ ) to  $2.36$ ,  $2.81$  and  $3.58 \text{ Mg ha}^{-1}$  with  $M_1$ ,  $M_2$  and  $M_3$  treatments; and from  $2.44 \text{ Mg ha}^{-1}$  with 33 per cent of recommended NK ( $F_1$ ) to  $2.69$  and  $2.91 \text{ Mg ha}^{-1}$  with 66 ( $F_2$ ) and 100 per cent ( $F_3$ ) of recommended NK, respectively.

The interaction effects during 1997 showed that highest grain yield ( $3.71 \text{ Mg ha}^{-1}$ ) was obtained with  $M_3F_3$ ; it was statistically at par with the yield obtained with  $M_3F_2$  ( $3.57 \text{ Mg ha}^{-1}$ ) and  $M_3F_1$  ( $3.48 \text{ Mg ha}^{-1}$ ) treatment. The grain yield produced with  $M_2F_1$  ( $2.33 \text{ Mg ha}^{-1}$ ) was statistically the same as with  $M_0F_2$  ( $1.96 \text{ Mg ha}^{-1}$ ),  $M_0F_3$  ( $2.13 \text{ Mg ha}^{-1}$ ) and  $M_0F_3$  ( $2.50 \text{ Mg ha}^{-1}$ ) treatments. The lowest grain yield ( $1.77 \text{ Mg ha}^{-1}$ ) was obtained with  $M_0F_1$  treatment.

The straw yield followed the similar trend as the grain yield. It increased from  $6.47 \text{ Mg ha}^{-1}$  in control ( $M_0$ ) to  $9.10$ ,  $10.14$  and  $11.16 \text{ Mg ha}^{-1}$  with  $M_1$ ,  $M_2$  and  $M_3$  treatments, respectively. The effect of fertilizer treatments on rice straw yield was also significant. The rice straw was  $8.82$ ,  $9.16$  and  $9.88 \text{ Mg ha}^{-1}$  with  $F_1$ ,  $F_2$  and  $F_3$  fertilizer levels, respectively. The interaction effects showed that the highest straw ( $11.20 \text{ Mg ha}^{-1}$ ) was produced with  $M_3F_2$  treatment and it was statistically at par with  $M_3F_3$  ( $11.16 \text{ Mg ha}^{-1}$ ) and  $M_3F_1$  ( $11.11 \text{ Mg ha}^{-1}$ ) treatments. The straw yield with  $M_2F_1$  ( $9.47 \text{ Mg ha}^{-1}$ ) was statistically same with  $M_1F_3$  ( $9.07 \text{ Mg ha}^{-1}$ ) and  $M_1F_2$  ( $9.06 \text{ Mg ha}^{-1}$ ) treatments. The lowest straw yield ( $5.43 \text{ Mg ha}^{-1}$ ) was produced with  $M_0F_1$  treatment.

**4.3.3.2 Wheat Yield :** Wheat grain yield was significantly affected by main as well as interaction effects of lantana and fertilizer levels during both the years (Table 17). During

1996-97, the wheat grain yield was 1.52 Mg ha<sup>-1</sup> without lantana (M<sub>0</sub>), which increased to 1.61, 1.77 and 1.83 Mg ha<sup>-1</sup> with 10, 20 and 30 Mg lantana ha<sup>-1</sup>, respectively. The grain yield was statistically same with M<sub>0</sub> and M<sub>1</sub> treatments. The grain yield was 1.50, 1.70 and 1.85 Mg ha<sup>-1</sup> with '50 per cent of recommended NPK to rice + 75 per cent of recommended NPK to wheat' (F<sub>1</sub>), '75 per cent of recommended NPK to each rice and wheat' (F<sub>2</sub>) and '100 per cent of recommended NPK to rice + 75 per cent of recommended NPK to wheat' (F<sub>3</sub>), respectively.

Interaction effects of lantana and fertilizer levels on grain yield of wheat were also significant. Significantly highest grain yield of 1.92 Mg ha<sup>-1</sup> was obtained with M<sub>3</sub>F<sub>3</sub> treatment, whereas, the grain yield of wheat with M<sub>3</sub>F<sub>1</sub> treatment (1.78 Mg ha<sup>-1</sup>) was statistically at par with M<sub>2</sub>F<sub>3</sub> (1.88 Mg ha<sup>-1</sup>), M<sub>2</sub>F<sub>2</sub> (1.78 Mg ha<sup>-1</sup>), M<sub>1</sub>F<sub>3</sub> (1.80 Mg ha<sup>-1</sup>) and M<sub>0</sub>F<sub>3</sub> (1.80 Mg ha<sup>-1</sup>) treatments. The lowest grain yield (1.22 Mg ha<sup>-1</sup>) was obtained with M<sub>0</sub>F<sub>1</sub>, which was at par with M<sub>1</sub>F<sub>1</sub> (1.35 Mg ha<sup>-1</sup>) treatment.

During 1997-98 almost similar trends in wheat grain yield were observed (Table 17). The grain yield was 1.99 Mg ha<sup>-1</sup> with M<sub>0</sub> treatment which increased to 2.31, 2.46 and 2.76 Mg ha<sup>-1</sup> with M<sub>1</sub>, M<sub>2</sub> and M<sub>3</sub> treatments, respectively. The yield was statistically same with M<sub>1</sub> and M<sub>2</sub> treatments. Averaging over lantana rates, grain yield was 2.22, 2.38 and 2.54 Mg ha<sup>-1</sup> with '33 per cent of recommended NK to rice + 66 per cent of recommended NPK to wheat' (F<sub>1</sub>), '66 per cent of recommended NK to rice + 66 per cent of recommended NPK to wheat' (F<sub>2</sub>) and '100 per cent of recommended NK to rice + 66 per cent of recommended NPK to wheat' (F<sub>3</sub>), respectively.

The interaction effects of lantana and fertilizer levels were also significant. The highest grain yield of 2.96 Mg ha<sup>-1</sup> was obtained with M<sub>3</sub>F<sub>3</sub>, which was statistically at par with M<sub>3</sub>F<sub>2</sub> (2.75 Mg ha<sup>-1</sup>), M<sub>3</sub>F<sub>1</sub> (2.68 Mg ha<sup>-1</sup>) and M<sub>2</sub>F<sub>3</sub> (2.70 Mg ha<sup>-1</sup>) treatments. The

Table 17 Effect of lantana biomass on wheat yields during ninth and tenth rice-wheat cropping cycle

Treatment (Lantana, Mg ha <sup>-1</sup> )	Grain Yield (Mg ha <sup>-1</sup> )					Straw Yield (Mg ha <sup>-1</sup> )											
	1996-97		1997-98			1996-97		1997-98									
	F <sub>1</sub>	F <sub>2</sub>	F <sub>3</sub>	Mean	F <sub>1</sub>	F <sub>2</sub>	F <sub>3</sub>	Mean	F <sub>1</sub>	F <sub>2</sub>	F <sub>3</sub>	Mean					
0	1.22	1.53	1.80	1.52	1.93	2.00	2.05	1.99	1.65	1.83	1.93	1.81	2.65	2.95	3.03	2.88	
10	1.35	1.68	1.80	1.61	2.02	2.35	2.57	2.31	2.32	2.45	2.60	2.46	3.15	3.55	4.11	3.57	
20	1.63	1.78	1.88	1.77	2.25	2.43	2.71	2.46	2.20	2.57	2.80	2.53	3.22	3.92	4.10	3.74	
30	1.78	1.80	1.92	1.83	2.68	2.75	2.86	2.76	2.45	2.73	3.32	2.83	3.73	4.15	4.34	4.08	
Mean	1.50	1.70	1.85	1.68	2.22	2.38	2.54	2.15	2.15	2.40	2.67	2.46	3.19	3.64	3.87	3.19	
LSD (P = 0.05)	Lantana			= 0.11					= 0.22				= 0.24				
	Fertilizer			= 0.09					= 0.19				= 0.19				
	Lantana × fertilizer			= 0.18					= 0.41				= 0.48				

Note : During 1996-97,

F<sub>1</sub> = 50 % of recommended NPK to rice + 75 % of recommended NPK to wheat

F<sub>2</sub> = 75 % of recommended NPK to rice + 75 % of recommended NPK to wheat

F<sub>3</sub> = 100 % of recommended NPK to rice + 75 % of recommended NPK to wheat

During 1997-98,

F<sub>1</sub> = 33 % of recommended NK to rice + 66 % of recommended NPK to wheat

F<sub>2</sub> = 66 % of recommended NK to rice + 66 % of recommended NPK to wheat

F<sub>3</sub> = 100 % of recommended NK to rice + 66 % of recommended NPK to wheat

grain yield obtained with  $M_2F_1$  ( $2.25 \text{ Mg ha}^{-1}$ ) was statistically same as with  $M_1F_1$  ( $2.02 \text{ Mg ha}^{-1}$ ),  $M_0F_2$  ( $2.00 \text{ Mg ha}^{-1}$ ) and  $M_0F_3$  ( $2.05 \text{ Mg ha}^{-1}$ ) treatments. The lowest grain yield ( $1.93 \text{ Mg ha}^{-1}$ ) was obtained with  $M_0F_1$ , which was at par with  $M_0F_2$  ( $2.00 \text{ Mg ha}^{-1}$ ),  $M_0F_3$  ( $2.05 \text{ Mg ha}^{-1}$ ) and  $M_1F_1$  ( $2.02 \text{ Mg ha}^{-1}$ ) treatment.

The straw yield of wheat was also affected significantly by all the treatments and their interactions (Table 17). During 1996 -97, the straw yield of wheat was 1.81, 2.46, 2.53 and  $2.83 \text{ Mg ha}^{-1}$  with  $M_0$ ,  $M_1$ ,  $M_2$  and  $M_3$  treatments; and 2.15, 2.40 and  $2.67 \text{ Mg ha}^{-1}$  with  $F_1$ ,  $F_2$  and  $F_3$  treatments, respectively. The interaction effects of lantana and fertilizer on straw yield of wheat were also significant. Like grain yield, the highest straw yield ( $3.32 \text{ Mg ha}^{-1}$ ) was produced with  $M_3F_3$ , and lowest ( $1.65 \text{ Mg ha}^{-1}$ ) with  $M_0F_1$  treatment.

During 1997-98 also the wheat straw yield was significantly affected by lantana and fertilizer treatments and their combinations. The straw yield was  $2.88 \text{ Mg ha}^{-1}$  with  $M_0$  treatment, and increased to 3.57, 3.74 and  $4.08 \text{ Mg ha}^{-1}$  with  $M_1$ ,  $M_2$  and  $M_3$  treatments, respectively. The straw yield with  $F_1$ ,  $F_2$  and  $F_3$  treatment was 3.19, 3.64 and  $3.87 \text{ Mg ha}^{-1}$ , respectively. The interactions among different lantana and fertilizer treatments were also significant and the highest straw yield of  $4.34 \text{ Mg ha}^{-1}$  was obtained with  $M_3F_3$ , and lowest yield of  $2.65 \text{ Mg ha}^{-1}$  with  $M_0F_1$  treatment.

**4.3.3.3 Total Productivity of 'Rice + Wheat' Cropping System :** The total productivity, i.e. the grain yield of 'rice + wheat' followed the similar trend as the grain yield of individual crops of rice and wheat (Table 18). The total productivity was calculated only for the year 1997-98. The incorporation of lantana @ 10 ( $M_1$ ), 20 ( $M_2$ ) and 30 ( $M_3$ )  $\text{Mg ha}^{-1}$  increased the total productivity of the system from  $3.95 \text{ Mg ha}^{-1}$  in control ( $M_0$ ) to 4.68, 5.24 and  $6.35 \text{ Mg ha}^{-1}$ , respectively. The total production with chemical fertilizers @ 33 per cent ( $F_1$ ), 66

per cent ( $F_2$ ) and 100 per cent ( $F_3$ ) of recommended NK to rice plus a uniform dose of 66 per cent of recommended NPK to wheat, was 4.65, 5.68 and 5.95  $\text{Mg ha}^{-1}$ , respectively.

The interaction effects of lantana and fertilizer were also significant on total productivity. The highest crop production was observed in  $M_3$  treated plots, irrespective of fertilizer levels. The values of total grain yield were 6.16, 6.32 and 6.57  $\text{Mg ha}^{-1}$  in  $M_3F_1$ ,  $M_3F_2$  and  $M_3F_3$  treated plots, respectively, which were statistically at par. The total grain yield produced by  $M_1F_1$  (4.21  $\text{Mg ha}^{-1}$ ) was statistically same as with  $M_0F_3$  (4.18  $\text{Mg ha}^{-1}$ ) treatment. The lowest grain yield (3.70  $\text{Mg ha}^{-1}$ ) was obtained with  $M_0F_1$  treatment.

Table 18 Effect of ten annual applications of lantana biomass on total productivity of 'rice + wheat' during 10<sup>th</sup> rice-wheat cropping cycle

Treatment (Lantana, $\text{Mg ha}^{-1}$ )	'Rice + wheat' grain yield ( $\text{Mg ha}^{-1}$ ) 1997-98			
	$F_1$	$F_2$	$F_3$	Mean
0	3.71	3.96	4.18	3.95
10	4.21	4.75	5.07	4.68
20	4.50	5.24	5.99	5.24
30	6.16	6.32	6.57	6.35
Mean	4.65	5.68	5.95	
LSD ( $P = 0.05$ )	Lantana	= 0.26		
	Fertilizer	= 0.21		
	Lantana $\times$ fertilizer	= 0.49		

Note  $F_1$  = 33 % of recommended NK to rice + 66 % of recommended NPK to wheat  
 $F_2$  = 66 % of recommended NK to rice + 66 % of recommended NPK to wheat  
 $F_3$  = 100 % of recommended NK to rice + 66 % of recommended NPK to wheat

#### 4.4 Non-Limiting Water Range

Non-limiting water range (NLWR) was determined by using the data of soil penetration resistance (Fig. 4) and air-filled porosity of 0.15- 0.18 m soil layer (Fig 13 ). The volumetric moisture content corresponding to 10 per cent air-filled porosity (upper limit of NLWR) and 2 MPa soil penetration resistance (lower limit of NLWR), and corresponding

NLWR values under different treatments are given in Table 19. According to these data, the moisture content corresponding to 10 per cent air-filled porosity increased, while moisture content corresponding to 2 MPa soil penetration resistance decreased with the increasing rates of lantana addition. Consequently the NLWR, which is the difference in moisture content between two limits, increased with increase in the amount of lantana added. The NLWR values were 4.35, 7.43, 10.89 and 15.04 per cent soil moisture (volume-basis) in control and plots treated with 10, 20 and 30 Mg lantana ha<sup>-1</sup>, respectively.

Table 19 Effect of ten annual applications of lantana biomass on non-limiting water range (NLWR) determined during wheat cropping season

Treatment (Lantana, Mg ha <sup>-1</sup> )	Moisture Content (% m <sup>-3</sup> m <sup>-3</sup> ) at		
	10% air-filled porosity	2 MPa SPR*	NLWR
0	31.21	26.86	4.35
10	32.22	24.79	7.43
20	33.85	22.96	10.89
30	34.67	19.63	15.04
LSD (P = 0.05)	1.04	1.21	1.04

\* Soil penetration resistance

The NLWR was linearly, positively and significantly correlated with grain yield of wheat (Fig 17, Appendix IX). The following relationship between NLWR ( per cent, soil moisture) and grain yield of wheat (GY, Mg ha<sup>-1</sup>) was obtained.

(N = 12, 4.10 NLWR 15.86)

$$GY = 1.78 - 0.07 \text{ NLWR}; \quad r = 0.858^{**} \quad (4.23)$$

#### 4.5 Distinguishing Between Effects of Physical and Chemical Properties of Soil on Wheat Yield

The grain yield of wheat grown simultaneously in the field and polybags kept adjoining to the experimental site, are shown in Table 20. The grain yield of wheat under

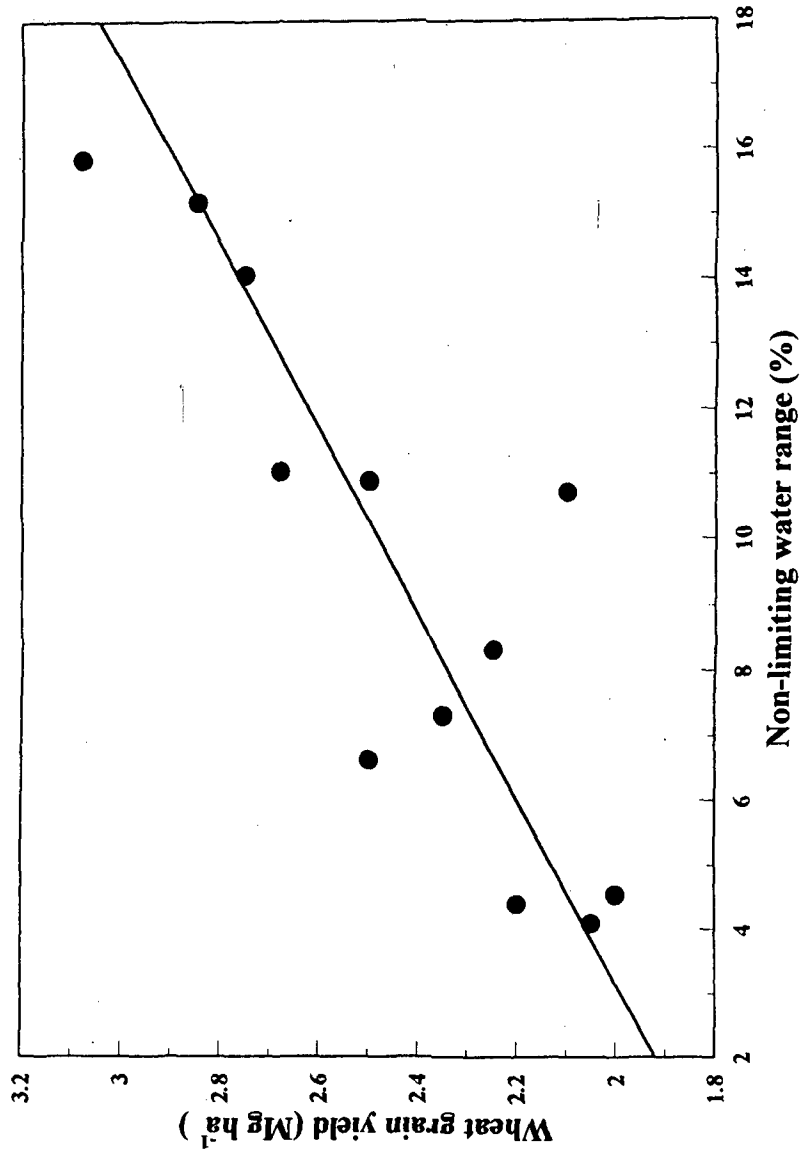


Figure 17. Relationship between non-limiting water range and wheat grain yield

field conditions was affected by both chemical and physical properties, while in polybags, wheat yield was influenced only by chemical properties of soil (because the soil physical properties in all polybags, filled with crushed and sieved soil samples at the same bulk density, was the same).

The per cent increase in grain yield of wheat over control with different treatments in the field was 11.6-13.9 per cent, while in polybags it was 10.5-12.7 per cent. The comparison of these data showed that per cent increase in grain yield due to lantana treatment in the field was higher than in polybags by 0.5-1.2. This increase in grain yield of wheat was attributed to improvement in various soil physical properties. Considering improvement in grain yield of wheat in the field due to lantana treatment over control (column I) as 100 per cent, the contribution of soil physical properties towards increase in grain yield amounted to 4.0-9.5 per cent (Table 20). In other words, only 4.0-9.5 per cent increase in grain yield of wheat was attributed to the improvement in soil physical properties, and the rest to improvement in soil chemical (and possibly biological) properties of soil due to addition of lantana biomass.

Table 20 Comparison of grain yield of wheat in the field treated with different lantana levels and in polybags filled with soil collected from the corresponding plots

Treatment (Lantana, Mg ha <sup>-1</sup> )	Wheat grain yield		Per cent increase in grain yield over control		Difference	
	Field (Mg ha <sup>-1</sup> )	Polybags (g bag <sup>-1</sup> )	Field (I)	Polybag (II)	(I - II)	% of (I)
0	1.99	14.83	—	—	—	—
10	2.31	15.56	11.6	10.5	1.1	9.5
20	2.46	17.58	12.4	11.9	0.5	4.0
30	2.76	18.83	13.9	12.7	1.2	8.6
LSD (P = 0.05)	0.16	1.34	—	—	—	—



# DISCUSSION

## V DISCUSSION

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Long-term additions of organic residues influence soil physical properties by adding organic matter to soil having low bulk density, high porosity, high water retention and high specific surface area, and its interaction with soil particles forming clay-organic complexes. Due to regular additions of organic residues, soil contains organic matter (OM) at different stages of its decomposition, including fresh material, decomposing material and decomposed material which has converted into soil humus. The decomposition of organic residues of soils and build-up of soil OC depend on many factors like nature, amount, frequency and mode of application of organic material, cropping sequence, and soil and environmental conditions. In the present long-term field experiment, fresh lantana (*Lantana camara*) biomass @ 10-30 Mg ha<sup>-1</sup>, is being used as an organic amendment in soil under rice-wheat cropping. The effect of ten annual additions of lantana biomass on OC build-up, soil physical properties and crop yields are discussed under the following heads :

### 5.1 Soil Organic Carbon Content

### 5.2 Soil Physical Properties

#### 5.2.1 Soil Colour and Temperature

#### 5.2.2 Structural Properties

##### 5.2.2.1 Soil Aggregation

##### 5.2.2.2 Bulk Density, Porosity and Pore-size Distribution

##### 5.2.2.3 Soil Penetration Resistance

##### 5.2.2.4 Degree of Puddling

##### 5.2.2.3 Coefficient of Linear Extensibility, Cracking Behaviour and Clod-Size Distribution

#### 5.2.3 Hydraulic Properties

##### 5.2.3.1 Soil-Water Retention and Availability

#### 5.2.3.2 Soil-Water Transmission Properties

#### 5.2.3.3 Drying Pattern of Soil

#### 5.2.3.4 Air-Filled Porosity

### 5.2.4 Mechanical Properties

#### 5.2.4.1 Soil Consistency Limits

#### 5.2.4.4 Clod Breaking Strength and Energy Required for Land Preparation for Wheat

### 5.5 Crop Performance

#### 5.3.1 Root and Shoot Growth

#### 5.3.2 Crop Yields

#### 5.4 None-Limiting Water Range – A Single Value Physical Index

## 5.1 Soil Organic Carbon Content

Ten annual applications of lantana significantly increased the OC content of surface ( 0-0.15 m ) and subsurface (0.15-0.30 m ) soil layers (Table 3). A total of 17.8, 35.6 and 54.4 Mg ha<sup>-1</sup> OC was added over a period of ten years to 0-0.15 m soil layer through lantana @ 10, 20 and 30 Mg ha<sup>-1</sup> year<sup>-1</sup>, respectively. Out of this only 3.0, 4.1 and 6.7 Mg OC ha<sup>-1</sup> was retained in 0-0.15 m soil layer; and 2.8, 4.3 and 6.5 Mg OC ha<sup>-1</sup> in 0.15-0.30 m soil layer. It amounted to 17, 11 and 12 per cent increase in OC over control in surface and 15, 11 and 12 per cent increase in OC in subsurface soil layer respectively. During tenth cropping cycle, the OC content of plots treated with zero, 10, 20 and 30 Mg ha<sup>-1</sup> lantana was 11.1, 12.5, 13.0 and 14.02 g kg<sup>-1</sup> in surface layer , and 7.6, 8.9, 9.6 and 10.6 g kg<sup>-1</sup> in subsurface soil layer, respectively. Considering 0-0.30 m soil layer as a whole, 33, 23 and 24 per cent of added OC was retained in soil. These data lead to the conclusion that (i) only a small fraction of applied OC is retained by the soil; a major part is lost to the atmosphere during its decomposition process, and (ii) the retention of OC in soil is not proportional to the amount of OC added; the

fraction of OC retained by soil decreased with the increase in the amount of OC added. These data also suggest that large additions of organic residues continuously over a period of time are required to cause a significant build-up in soil OC.

A major portion of the added OC is lost from soil to the atmosphere probably through carbondioxide (CO<sub>2</sub>) or methane (CH<sub>4</sub>) evolution. Alternate wetting (during rice season) and drying (during wheat season) of soil enhance OC losses from soil (Amato *et al.*, 1984). In a laboratory incubation study, Rasmussen and Collins (1991) reported that 60 to 75 per cent of the crop residue-carbon is evolved as CO<sub>2</sub> in one year. Our results are in line with Brar and Dhillon (1994), who detected only 8.1 per cent of 32 Mg OC ha<sup>-1</sup> applied through FYM over a period of 4 years in a rice-wheat cropping under sub-tropical conditions.

MacRae and Mehuys (1985) reported that if soil-OC levels are to be increased or maintained, the organic material added to the soil must be resistant to ready decomposition. According to Warman (1980), the plant materials low in nitrogen (< 1.5 per cent N on dry mass basis) are most effective for this purpose. The nitrogen content of lantana biomass was 2.5 per cent (Table 2) and the C:N was around 20:1. Relatively high N content and narrow C:N ratio probably were responsible for rapid decomposition and, hence, loss of added OC to the atmosphere and less retention in soil. Any waste organic material having lower N content, and wider C:N ratio than lantana biomass may prove more effective in a rising the OC content of soil. Substantial increases in OC are required before improvements in soil physical properties become visible. In the present experiment, the increase in OC in 0-0.30 m soil layer was sufficient to cause significant effects on soil physical properties.

## 5.2 Soil Physical Properties

### 5.2.1 Soil Colour and Temperature

The addition of lantana made the soil dark by changing the value and chroma of the soil; hue remained unchanged. When observed under dry conditions, soil colour changed from brownish yellow (10 YR 6/6) in control to light yellowish brown (10 YR 6/4) in lantana-treated plots (Table 4). Under moist conditions, soil colour was yellowish brown (10YR 5/4) in control, which changed to brown (10 YR 5/3) with 10 Mg ha<sup>-1</sup> and dark brown (10YR 4/3) with 20 and 30 Mg lantana ha<sup>-1</sup>. The change in colour of the surface soil layer influenced the soil thermal regime probably by increasing black-body effect and decreasing the albedo. The soil temperature recorded at 0.05 m soil depth on Dec. 30, 1997 (one of the coldest days) at 06.30 h (minimum) was 5.4°C in control plots as compared to 5.6, 5.7 and 5.7°C in plots treated with 10, 20 and 30 Mg lantana ha<sup>-1</sup>, respectively. Likewise, maximum temperatures recorded at 14.30 h were 11.9, 12.2, 12.3 and 12.5°C in control and lantana-treated plots, respectively (Table 4). Even small changes in soil temperature have profound effect on crop growth and yield (Walker, 1969).

### 5.2.2. Structural Properties

**5.2.2.1 Soil Aggregation :** Lantana additions significantly influenced the water-stability of soil aggregates, expressed as mean weight diameter (MWD) and water stable aggregates (WAS) > 0.25 mm dia. At any time during rice cropping season, MWD in treated plots was 27-203 per cent higher than the control depending on the rate of lantana added (Table 5). The similar trend was observed in case of WAS > 0.25 mm dia. Increase in soil OC improves soil aggregation by way of forming clay-organic complexes in soil (Greenland, 1965). In temperate

regions, OC has been found to be the primary aggregate stabilising agent. Much of the applied OC remains in soil as discrete particles and only a part of it enters into close association with soil particles (Sharma *et al.*, 1995). Tisdall and Oades (1982) concluded that micro aggregates (< 0.25 mm dia) are less susceptible to changes in soil OC than macro aggregates. It may take many years of regular additions of organic residues for the added OC to enter and stabilise micro aggregates (Christensen, 1986).

Soil aggregation during rice cropping season increased progressively with time elapsed after puddling in all the plots (Table 5); the effect increased with the increase in amount of lantana added. Chaudhary and Ghildyal (1969) reported that soil structure lost during puddling is not only regenerated, but is further improved during crop growth under submerged conditions. It may result from settling of soil particles, intermittently dehydration of soil particles due to wetting and drying of soil and /or formation of clay-organic complexes with time, especially in the presence of high amounts of organic matter (OM).

A positive correlation of aggregate stability with OC has been shown by many workers (Biswas *et al.*, 1970; Sharma and Aggarwal, 1984; Christensen, 1986; Bhagat and Verma, 1991; Sharma *et al.*, 1995).

**5.2.2.2 Bulk Density, Porosity and Pore-Size Distribution :** The bulk density of whole soil (0-0.30 m soil depth), soil aggregates (2-8 mm dia ) and soil clods (4-6 cm dia) decreased significantly with the addition of lantana biomass (Fig. 1, Table 6). The decrease in bulk density over control was 6-19 per cent in 0-0.15 m soil layer, 2-6 per cent in 0.15-0.30 m soil layer, 7-14 per cent in soil aggregates, and 4-9 per cent in soil clods, depending on the rates of lantana application. Reduction in soil bulk density resulted from the dilution of soil matrix (mineral

matter) with less dense material (organic matter) and improvement in soil aggregation. The bulk density of OM is much lower than inorganic mineral matter. Improvement in aggregation encourages a fluffy and porous condition in soil which results in low bulk density values. The reduction in bulk density of soil due to increase in soil OC has been amply reported in literature (Soane, 1975; Coote and Ramsey, 1983; Sharma and Aggarwal, 1984; Sharma *et al.*, 1995).

The data show that the decrease in bulk density was more in whole soil as compared to soil aggregates and soil clods. It may be due to the fact that a bulk of applied lantana biomass (decomposed, partially decomposed and undecomposed) remained in soil and only a small fraction of it entered in aggregates and clods as organic carbon. Moreover, the clods are formed due to compressive forces exerted on soil during tillage operations. Further, decrease in bulk density was more in 0-0.15 m soil layer than in 0.15-0.30 m soil layer, again due to the reason that the lantana biomass applied was remained in the surface soil layer, and a part of it probably moved into the subsoil after decomposition. Moreover, the long-term additions of lantana biomass increased the volume of the soil, thereby, causing lengthening of surface layer. Since, the bulk density determinations were made in the top 0-0.15 m, a part of the lengthened soil layer beyond 0.15 m depth was included in subsurface layer.

The lantana additions did not significantly affect particle density of soil. The average particle density value was 2.44 ( $\pm 0.02$ ) Mg m<sup>-3</sup>. Hence, the total porosity of whole soil, soil aggregates and soil clods, which was computed from their particle and bulk density values, increased with the lantana additions. The per cent increase in total porosity of whole soil, soil aggregates and soil clods observed at rice harvest was 9-27, 13-21 and 15-16 over control, respectively, depending on the rate of lantana added (Table 7). Similar trend in total porosity of

0-0.075 m soil layer were observed at 30 DAT of rice, rice harvest and 30 DAS of wheat (Fig. 2).

The pore-size distribution in 0-0.075 m soil layer, as per the classification suggested by Greenland (1979), is shown in Fig. 3. At all the three stages of observations, i.e. during rice crop, at rice harvest and during wheat crop, the water transmission pores (pores  $> 50 \mu\text{m}$ ) generally increased, residual pores ( $< 0.5 \mu\text{m}$ ) decreased, while the water storage pores ( $0.5-50 \mu\text{m}$ ) either remained almost same as during rice cropping season, or increased with lantana additions. The increased in water transmission pores in soil due to lantana additions might have resulted from large amount of undecomposed material lying in soil and formation of channels due to decomposition of organic material. Increase in soil aggregation was probably responsible for the reduction in residual pores, because more of the intra-aggregate pore space acts as water storage pores. This increase in water storage pores was probably offset due to the conversion of water storage pores into water transmission pores as the inter-aggregate pore space. Such changes in pore-size distribution would favour plant-available water capacity and improved drainage conditions of soil.

**5.2.2.3 Soil Penetration Resistance :** Soil penetration resistance (SPR) is a measure of resistance that must be overcome to cause a deformation in soil. In a given soil type, it depends largely on moisture content and bulk density. The SPR decreases with moisture content and increases with bulk density (Kumar *et al.*, 1971; Kisu, 1978). Increase in bulk density increases the resistance of soil to, both, volumetric compression and linear deformation. Any treatment which decreases bulk density is expected to lower SPR. It was clearly demonstrated by the SPR data collected in the present experiment. The SPR in the plough layer (at 0.075 and 0.15 m) was

highest in control and it decreased progressively with the application of lantana biomass @ 10-30 Mg ha<sup>-1</sup>. The application of lantana decreased bulk density (Fig. 1, Table 3) and thereby decreased SPR. Reduction in SPR due to decrease in bulk density of soil have also been reported by earlier workers (Ganai and Singh, 1988; Bhagat and Verma, 1991).

The SPR was linearly, negatively and significantly correlated with moisture content at each level of lantana biomass at both the depths (Fig. 4, eqns. 4.1-4.8). The SPR decreased with the moisture content because increase in moisture content decreases the inter-particle binding and the soil can be easily deformed. The reduction in SPR with decrease in moisture content is well documented in literature (Bateman *et al.*, 1965; Gu and Wen, 1981; Larson and Clapp, 1984; Tester, 1990).

Increase in SPR due to wet tillage in rice is a common observation and offers major constraint in the cultivation of upland crops after rice. Application of lantana, thus, decreased this problem in rice-wheat sequence.

**5.2.2.4 Degree of Puddling :** The degree of puddling of soil during rice transplanting, as expressed by puddling index and change in apparent specific volume ( $\Delta$  ASV), was significantly affected by lantana biomass (Table 8). The degree of puddling depends on the ease with which the aggregates can be broken down and the saturation soil moisture content. Application of lantana decreased soil bulk density and made soil friable, as was reflected from the data on SPR (Fig. 4) and clod breaking strength (Fig. 16). Soil water content at saturation also increased with the lantana due to increase in total porosity of soil. These effects resulted into increased degree of puddling. Fagi and De Datta (1983) also reported increase in  $\Delta$  ASV in a rice soil supplied with the residues of previous crops of soybean and maize. According to

these workers,  $\Delta$  ASV was significantly and positively correlated with change in soil porosity. It very well corroborated our findings.

Higher values of  $\Delta$  ASV and puddling index in lantana-treated than in control plots reflected the increase in susceptibility of soil to puddling. It reflects the quality of soil puddle for transplanting rice seedlings and water retention in rice fields. The  $\Delta$  ASV of puddled soil may increase the soil tortuosity for water movement which in turn reduces the percolation and evaporation losses of soil water. Lantana applications, thus, favoured rice cultivation.

#### **4.2.2.5 Coefficient of Linear Extensibility, Cracking Behaviour and Clod-size distribution :**

The nature and extent of soil cracking depends on swell-shrink properties of surface soil. The OC build-up in soil due to lantana additions significantly affected cracking behaviour of soil by changing its coefficient of linear extensibility (COLE). Application of lantana increased COLE value from 0.070 cm cm<sup>-1</sup> in control plots to 0.097-0.116 cm cm<sup>-1</sup> in lantana-treated plots (Table 8). The increase in COLE due to the addition of OM into the soil probably resulted from high swell-shrink properties of organic matter. The soils with COLE value of 0.090 cm cm<sup>-1</sup> or greater are placed in Vertic Sub Group (Lewis, 1979). Even though these soils lack the intensity of swell-shrink necessary to place them in Vertisol Sub Group, the amount of volume change that occurs on wetting and drying presents management problems that are serious enough to warrant setting these soils aside from others that lack high swell-shrink tendency. The COLE data, thus, shows that application of lantana increased Vertic properties of the experimental soil. It was also indicated by the moisture content at which hair-line cracks started appearing on the soil surface. The hair-line cracks started appearing at moisture content of

39.9, 42.5 and 44.1 per cent in 10, 20 and 30 Mg ha<sup>-1</sup> lantana-treated plots, respectively, as compared to 33.7 per cent in control.

Application of lantana modified cracking pattern from almost hexagonal-shaped wide cracks in control to close-spaced network of fine cracks (Plate 1). The proportion of finer cracks (< 5mm width) increased at the expense of wider cracks with lantana treatments; the effect increased with the amount of lantana added. In response to decrease in width of cracks, the depth, surface area and volume of cracks decreased with lantana additions. The values were in the order of  $M_0 > M_1 > M_2 > M_3$  (Fig. 5, 6, 7 and 8, eqn. 4.9). The depth of cracks was linearly, positively and significantly correlated with width of cracks (Fig. 7). Due to this there was significant decrease in the total surface area exposed to evaporation in lantana-treated plots. In control, the wider and deep cracks provided secondary planes of evaporation, thereby increasing the evaporation losses.

The cracking pattern affects, both, the extent and size-distribution of clods formed when the soil is tilled, and the hydrodynamic properties of the soil. Application of lantana decreased the proportion of large-sized clods (> 2 cm dia), and increased small-sized clods ( $\leq 2$  cm dia); the clods > 6 cm dia were found only in control plots (Table 9). Large clods in control plots were associated with wider and deep cracks. Conversely, close network of fine cracks in lantana-treated plots favoured the smaller clods. Further, the application of lantana increased the plastic limit from 27.2 to 28.5-30.6 per cent (discussed in para 5.2.4.1), which is the upper limit of friability of soil. The tillage was done at 29.6 ( $\pm 2.7$ ) per cent soil moisture content when the soil in control was above the plastic limit while in 20-30 Mg ha<sup>-1</sup> lantana-treated plots it was below plastic limit. The tillage above plastic limit, moisture content favours clod

formation. This was also the reason for higher percentage of large clods in control plots. Lantana additions, thus, modified soil cracking behaviour in favour of reduced clod formation.

### 5.2.3 Hydraulic properties

**5.2.3.1 Soil-Water Retention and Availability :** Soil-water retention at all suction values from 0-1500 kPa, when expressed on mass-basis, increased progressively with the amount of lantana added. Same trend was observed during rice season, at rice harvest and during wheat season (Fig. 9). However, the trend was reversed, when soil water retention was expressed on volume-basis; the water retention above about 50 kPa suction was always lower in lantana-treated than control plots (Table 10).

Water retention capacity of soils depends principally on, (i) the number and size-distribution of soil pores and (ii) the specific surface area of soils. Pore-size distribution affects soil water retention primarily at lower suction values, while water retention at higher values is influenced by specific surface area of soil constituents. The OM affect both these soil properties. It increases soil pores favourable for water retention (Fig. 2) and specific surface area of soils. The water holding capacity of OM is very high. When added to soil, it dilutes material of low water retention with that of high retention.

The plant-available water capacity (PAWC), which was computed as the difference in soil water content at 30 and 1500 kPa suction, was lower in control as compared to lantana-treated plots, when expressed on mass-basis (Table 10). The water retention increased with the amount of lantana added. The trend was same during rice season, at rice harvest and during wheat season. But, when PAWC was expressed on volume-basis, the trend was almost reversed. The PAWC on volume-basis decreased with lantana additions at rice harvest;

increased during wheat season, while remained same during rice season irrespective of lantana treatments.

The addition of OM to soil, although increases soil water retention, decreases soil bulk density. The decreased soil bulk density may counter balance any increase in PAWC on mass-basis. Therefore, when moisture content is computed on volume-basis, the increase in PAWC may be non-existent or PAWC may even decrease, as was observed in the present case. The decrease in soil bulk density due to lantana additions during rice season was such that it masked the increase in PAWC on volume-basis. At rice harvest, the decrease in bulk density was almost in proportion to increase in PAWC on mass basis and hence, PAWC on volume-basis decreased with lantana additions. During wheat season, however, the decrease in bulk density due to lantana additions was less than the PAWC on mass-basis and hence, PAWC on volume-basis showed the same (increasing) trend as PAWC on mass-basis. Relatively large changes in bulk density during rice season and at rice harvest were attributed to freshly added lantana biomass into surface soil layer. By the wheat season a major portion of added OM was probably decomposed and hence, its effect on bulk density was less than during rice season.

Many studies have shown positive correlation between PAWC and soil organic matter content, but they have computed the correlation using PAWC on mass-basis (Biswas and Ali, 1969; Epstein *et al.*, 1976; Gupta and Larson, 1979; Lal, 1979; De Kimpe *et al.*, 1982). These data may, however, lead to wrong conclusions, because the plant roots exploit the soil on volume-basis and not on mass-basis for extracting soil moisture. In order to evaluate the real effect of OM on PAWC, moisture content should be expressed on volume-basis. In the present

study, therefore, lantana additions increased PAWC (volume-basis) of soil during wheat season but did not show any effect on PAWC during rice season.

**5.2.3.2 Soil-Water Transmission Properties :** Two soil-water transmission properties, namely infiltration and saturated hydraulic conductivity ( $K_s$ ), were determined at rice and wheat harvest (Fig. 11 and 12; Table 11). Infiltration rate as well as  $K_s$  of soil increased significantly with the lantana additions. Application of lantana @ 10, 20 and 30 Mg ha<sup>-1</sup> showed 2, 4 and 8-fold increase in final infiltrability of soil over control at rice harvest, and 2, 3 and 5-fold increase at wheat harvest, respectively. The corresponding increases in  $K_s$  with three lantana rates were 1.3, 1.8 and 2.1-fold at rice harvest, and 1.4, 2.2 and 4.3-fold at wheat harvest, respectively.

The water transmission through soil is closely related to the pore-size distribution. Infiltration and  $K_s$  increase with water transmission pores of soil. In the present experiment also the increases in infiltrability and  $K_s$  were associated with the increase in water transmission pores due to lantana additions (Fig. 3). The infiltrability values at rice harvest may also be influenced by soil cracking. Soil cracking would enhance the infiltrability. However, in the present determinations due care was taken to avoid the effect of soil cracks.

**5.2.3.3 Drying Pattern of Soil :** Matric suctions at 0.15 as well as 0.30 m soil depths at were almost the same in all plots under different treatments until the harvest of rice crop. The effect of lantana treatments on soil drying became evident after the rice crop was harvested. The matric suction, in general, increased as a power function of time (eqns. 4.10-4.17). Lantana applications suppressed the rate of drying of soil upto 0.30 m soil depth (Fig. 15). The drying pattern of soil depends on soil-water retention and evaporation losses of water from soil. Applications of lantana on one hand, increased the soil water retention (Fig. 9) and on the other

hand, increased the soil water contact angle from  $70^\circ$  in control to  $76^\circ$  in  $30 \text{ Mg ha}^{-1}$  lantana-treated plots, thereby, making the soil more hydrophobic. Both these changes probably helped in lowering the evaporation rate from soil surface. Although the soil cracks started appearing relatively at higher moisture content in lantana treated plots, but majority of them were fine and superficial. Control plots developed wider and deeper cracks, which acted as secondary planes of evaporation, thereby increasing net evaporation losses from the soil. Consequently the rate of drying followed the trend of  $M_0 > M_1 > M_2 > M_3$ .

**5.2.3.4 Air-Filled Porosity :** Data on air-filled porosity collected after first irrigation to wheat at 30 DAS (Fig. 13 and 14) make two conclusions. One, air-filled porosity at any moisture content was higher in lantana-treated than control plots. Low and Piper (1973) also reported higher air-filled porosity (9.5 per cent) at field capacity in loamy soil treated with 6 consecutive applications of farm yard manure @  $75 \text{ Mg ha}^{-1}$ , than in control (8.3 per cent). Two, the 10 per cent air-filled porosity, considered critical for most of the upland crops, appeared much earlier in lantana-treated than in control plots. These effects increased with the increase in rate of lantana application. The effect of lantana on air-filled porosity of soil was manifested through increase in water transmission pores in soil. Lantana additions increased water transmission pores in soil by 22-29 per cent over control (Fig. 3). It helped in attainment of 10 per cent air-filled porosity in the active root-zone of wheat earlier in lantana-treated than in control plots. It has a greater significance in cultivation of wheat after rice. In our earlier experiment (Bhushan, 1995), inadequate air-filled porosity due to restricted drainage was found to be the major constraint to wheat cultivation in post-rice soil. Thus, application of lantana or

any other waste organic material to soil favour wheat cultivation by improving drainage conditions of soil.

#### 5.2.4 Mechanical Properties

**5.2.4.1 Soil Consistency Limits** : Soil consistency determines the workability of soil. The best moisture range for tillage is between plastic and shrinkage limits of the soil. In this range tillage of soil is friable. The plasticity index which is the difference between liquid and plastic limit indicates the moisture range through which soil has properties of plastic material. Utomo and Dexter (1981) observed that for some soils a gravimetric moisture content around 0.9 times the plastic limit provided the maximum friability. At this moisture content, soil tillage maximises the proportion of small aggregates (Ojeniyi and Dexter, 1979). The application of lantana increased the plastic limit, but decreased the friability range optimum for tillage (Table 12). Fagi and Datta (1983) also reported reduction in soil moisture range for ease of tillage due to the incorporation of crop residues in a sandy clay loam soil. Nevertheless, the lantana-treated soil became friable at fairly high moisture content because of increase in its plastic limit moisture content. The increase in plastic limit and shrinkage limit values with OM has been well documented in literature (Baver *et al.*, 1976). The COLE is an index of shrinkage behaviour of soil. Thus, the increase in shrinkage limit with OM is also supported by increase in COLE value (Table 8). The OM increased moisture content at all consistency limits resultant from the high absorptive capacity of OM for water. The increase particularly in plastic limit moisture content occurs because hydration of OM must be fairly complete before sufficient water is available for a film formed around the mineral particles, thereby, making the soil plastic.

**5.2.4.2 Clod Breaking Strength and Energy Required for Land Proportion :** The energy required for land preparation depends on the mechanical impedance of soil and clod breaking strength (CBS). Mechanical impedance of soil during tillage primarily depends on bulk density and moisture content at the time of tillage. Lantana applications decreased, both, bulk density of soil (Table 3) and CBS of clods (Fig. 16), thereby decreasing the energy required for land preparation (Table 13).

The CBS of clods was positively and linearly correlated with bulk density (Eqn. 4.22) and negatively and exponentially with moisture content of clods (Eqns. 4.18-4.21, Fig 16). Both, the moisture as well as bulk density, affect the inter-particle bonds within soil clods. Increase in moisture content decreases the inter particle bond through its lubricating effect. Higher bulk density increases the mechanical impedance towards clod crushing due to increased degree of compaction.

## **5.3 Crop Performance**

### **5.3.1 Root and Shoot Growth**

It is clear from the preceding discussion that application of lantana continuously over a period of 10 years, significantly improved soil physical properties. Earlier studies have shown that lantana applications also significantly improved soil chemical properties, including soil reaction and the status of available macro and micro nutrients (Sharma, 1996; Sharad, 1997). Improvement in soil productivity resulted into increase in crop growth and yield under rice-wheat cropping system. Cultivation of wheat after wet-land rice is generally adversely affected by higher mechanical impedance, unfavourable pore-size distribution and drainage problems in the root zone. Root growth of wheat in the present experiment significantly increased with the

amount of lantana applied (Plate 2, Table 14). The increase in RMD of wheat was possibly caused by reduction in soil penetration resistance (Fig. 4), increase in macro-pores (Fig. 3), increase in aeration porosity (Fig. 13 and 14) and regulation of favourable moisture regime in the root zone. The pore-size distribution is of significance to the root growth, because the diameter of roots of most of the cereal crops varies between 0.2 and 0.4 mm (Russell, 1977; Sharma 1979). The proportion of pores > 0.1 mm dia is usually restricted in soil. Application of lantana @ 10-30 Mg ha<sup>-1</sup> increased soil pores > 0.05 mm dia from 17 to 21-22 per cent as observed at 30 DAS of wheat. The roots are unable to penetrate the soil pores which are narrower than their root caps (Weirsum, 1957; Cannell, 1977). However, once the root has penetrated the soil pores, the continuation of root growth is possible if the roots are able to expand the pores by pushing aside soil particles, and hence is influenced by the rigidity of pore system. In a given soil, the rigidity of pore system is affected by the bulk density and moisture content. Lantana additions decreased bulk density (Fig. 1; Table 3) and increased the soil water retention (Fig. 9).

Literature shows that a definite relationship exists between root and shoot growth of plant and shoot/root ratio for a given crop is almost constant ( Gales, 1979; Yoshida, 1981). However, our earlier studies have shown that wheat shoot/root ratio is significantly affected by soil properties like bulk density, aeration status, soil water regime, status of available nutrients etc. ( Bhushan, 1995; Bhushan and Sharma, 1997). In the present study also, shoot/root ratio increased with the amount of lantana added (Table 15). These data show that improvement in soil environment due to lantana additions improves shoot growth more than root growth. Earlier studies also suggest that a relatively shallow root system can support a luxuriant shoot

growth if adequate nutrition, water and air are available in the root zone (Bhushan and Sharma, 1997). The effect of lantana further increased with the increased rates of chemical fertilizers. Increased nutrient availability at higher fertilizer rates was responsible for higher shoot/root ratio and the data are well supported by our earlier studies (Bhushan and Sharma, 1997).

### 5.3.2 Crop Yields

Improvement in physical and chemical properties of soil due to lantana additions increased grain and straw yields of both rice and wheat crops (Table 16 and 17). Grain yield of rice in 1997 increased by 21, 44 and 84 per cent over control, while the straw yield increased by 41, 57 and 72 per cent over control with lantana @ 10, 20 and 30 Mg ha<sup>-1</sup>, respectively (during 1996 the rice crop experienced neck blast infection). Similarly, wheat grain yield increased by 6, 16 and 20 per cent over control during 1996-97 and 16, 24 and 39 per cent over control during 1997-98, and straw yield increased by 36, 40 and 56 per cent over control during 1996-96 and 24, 30 and 42 per cent over control during 1997-98 with lantana @ 10, 20 and 30 Mg ha<sup>-1</sup>, respectively. A significant interaction between lantana and chemical fertilizer rates was observed for grain and straw yields of both the crops. The rice grain yield with recommended fertilizer (NK) was significantly lower than with 33 per cent of recommended NK + 30 Mg ha<sup>-1</sup> lantana; the yield was at par with 66 per cent of recommended NK + 20 Mg ha<sup>-1</sup> lantana (Table 16). The wheat grain yield in the plots treated with 20-30 Mg ha<sup>-1</sup> lantana + 33-50 per cent of recommended chemical fertilizers to rice was either higher or same as in plots receiving no lantana but only 100 per cent of recommended chemical fertilizers to rice (Table 17).

Data in Table 18. show that total grain production of rice + wheat (1997-98) with 30 Mg ha<sup>-1</sup> lantana + 33 per cent of recommended NK to rice was 1.98 Mg ha<sup>-1</sup> higher than in

plots receiving 100 per cent of recommended NK during rice season (all plots during wheat season received 66 per cent of recommended NPK); the yield was statistically at par with 20 Mg ha<sup>-1</sup> *lantana* + 33 per cent NK and 100 per cent of recommended NK but without *lantana* to rice.

The straw yields of both rice and wheat followed almost the same trend as the grain yields during both the years, i.e. 1996-97 and 1997-98.

These data clearly show that with the application of *lantana* biomass @ 20 Mg ha<sup>-1</sup> during rice season, it was possible to save chemical fertilizers to the tune of 67 per cent of the recommended. It will not only be economical but will have repercussions in terms of improved soil productivity on sustainable basis.

Studies have shown that the improvements in soil chemical properties, when studied independent of physical properties (para 3.6), substantially dominated the soil physical properties in their effect on crop yield. The contribution of improved soil physical properties towards increase in grain yield of wheat was 4-10 per cent, and those of chemical properties was 90-96 per cent (Table 20). However, since under field conditions plant is influenced by both physical and chemical properties simultaneously and their effects are additive, the contribution of physical properties in crop yield may be higher than 4-10 per cent as was observed in the present study. Nevertheless, these studies do suggest that the deterioration in physical properties of rice soil due to wet tillage, in relation to the following upland crop, need to be extensively and critically quantified so as to adopt suitable management practices for their amelioration.

#### **5.4 Non-Limiting Water Range – A Single Value Physical Index**

Soil physical properties in relation to plant growth may be broadly classified into two categories: one, those which directly influence the plant growth (by affecting direct properties), viz. water, oxygen, temperature and mechanical resistance in the root zone, and two, those which indirectly influence the plant growth, viz. bulk density, texture, aggregation, aggregate stability, pore-size distribution etc. The major complication in defining the suitability of soil physical properties to plant growth arises from the fact that the four soil physical properties directly affecting plant growth are inter-related and never independent of each other. It is impossible under field conditions to change the value of one factor without also changing the value of one or more of other factors. A balance between various soil physical properties is must for the optimum plant growth and yield.

Of the four physical properties directly influencing plant growth, water is dominant controlling factor. A change in water content causes a definite change in other three soil physical properties. Based on this fact, Letey,(1985) proposed “non-limiting water range” (NLWR) as a single value index for characterising the suitability of soil physical properties in relation to plant growth. According to this index the upper limit of water availability may not depend on field capacity but on aeration status in the root zone. If the aeration status is limiting for root growth at field capacity, a lower water content is required for adequate soil aeration and thus, the upper limit of plant availability will be lower than field capacity of soil. He used oxygen diffusion rate (ODR) to evaluate the aeration status of root zone. Similarly, the lower limit of plant water availability is decided by the soil penetration resistance in the root zone rather than the permanent wilting point (PWP), as the penetration resistance may become

limiting to root growth at a water content much higher than the PWP. The NLWR represents soil water range between critical soil aeration as the upper limit and soil penetration resistance as the lower limit. The NLWR decreases with poor aeration and/or high penetration resistance in the root zone. Higher the NLWR, better is the soil physical condition for plant growth and vice-versa.

We used moisture content at 10 per cent air-filled porosity as the upper limit in NLWR instead of ODR (oxygen diffusion rate) as suggested by Letey (1985). Air-filled porosity is relatively easy to determine. The application of lantana increased NLWR values from 4.35 per cent in control to 7.43-15.04 per cent, thereby indicating an improvement in soil physical properties in relation to wheat growth (Table 19). It was proved by significant correlation ( $r = 858^*$ ) between NLWR and wheat grain yield (Fig. 17, eqn 4.23). These data suggest that NLWR is a suitable single value physical index for characterising soil physical properties in relation to plant growth. It is simple, quantitative and feasible, as it necessitates the determination of only three soil properties, viz. aeration status (air-filled porosity or oxygen diffusion rate), soil penetration resistance critical for root growth (may be experimentally determined or referred from literature) and soil water content. Extensive testing of NLWR is needed to establish rating system of physical fertility of soil.



# SUMMARY

## VI SUMMARY

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Wheat yields in rice-wheat cropping are generally lower than in cropping sequences like maize-wheat, soybean-wheat etc. Deterioration in soil physical properties due to wet tillage in rice has largely been attributed to the decline in wheat yields. To improve and sustain wheat yield in rice-wheat cropping system, a long-term field experiment was established in June, 1987, in which fresh lantana biomass (*Lantana camara*) was used as an organic amendment. The lantana was applied @ 10, 20 and 30 Mg ha<sup>-1</sup> annually, 10-15 days before puddling and transplanting of rice. The objectives of the present study were to investigate changes in soil physical properties without and with lantana additions for ten years and their consequent effect on crop growth and yield. A single value physical index was also evaluated to assess the improvement in soil physical properties due to lantana additions.

Rice seedlings, 2-3 seedlings per hill (cv. HPU 2216 in 1996 and cv. HPR 976 in 1997) were transplanted during second week of July. Wheat (cv. Aradhana) was sown following rice during last week of November in 1996-97 and last week of December in 1997-98. The chemical fertilisers were applied @ 50, 75 and 100 per cent of recommended NPK to rice, and 75 per cent of recommended NPK to wheat during 1996-97; and 33, 66 and 100 per cent of recommended NK to rice, and 66 per cent of recommended NPK to wheat during 1997-98. The recommended rates of chemical fertilisers for rice are 90 N-18 P-33 K kg ha<sup>-1</sup> and for wheat are 120 N-39 P-25 K kg ha<sup>-1</sup>. Fresh lantana was chopped into 2-3 cm pieces and mixed in top 0-0.15 m moist soil layer manually before puddling.

Lantana applications significantly increased soil OC in surface (0-0.15 m) and subsurface (0.15-0.30 m) soil layers. The soil OC in lantana-treated plots increased from 11.1

(in control) to 12.5-14.2 g kg<sup>-1</sup> of soil in surface layer, and from 7.6 to 8.9-10.6 g kg<sup>-1</sup> of soil in subsurface soil layer. After ten annual applications of lantana @ 10-30 Mg ha<sup>-1</sup>, the surface layer retained 3.0-6.7 per cent, while subsurface layer retained 2.8-6.5 per cent of the total applied OC. It caused 13-28 and 17-39 per cent increase in soil OC over control in surface and subsurface soil layers. The build-up in soil OC triggered a series of changes in soil physical properties.

The colour of the surface soil layer changed from brownish yellow to light yellowish brown under dry conditions, and from yellowish brown to brown-dark brown under moist conditions with lantana applications. It influenced the soil temperature. When observed during last week of December, 1997, maximum temperature at 0.05 m soil depth was 11.9°C in control as compared to 12.2-12.5°C in lantana-treated plots, the minimum temperatures were 5.4°C and 5.6-5.7°C in control and lantana-treated plots.

The soil structural properties, characterised by soil aggregation, bulk density, total porosity, pore-size distribution, soil penetration resistance, degree of puddling, coefficient of linear extensibility (COLE), soil cracking behaviour and clod-size distribution, were significantly improved with lantana applications. Water stable aggregates (WSA) were determined as a function of time starting at 7 DAT of rice. The mean weight diameter (MWD) and WSA > 0.25 mm dia increased significantly with time after puddling and lantana additions; the effect increased with the amount of lantana added. MWD in control plots was 0.75 mm at 7 DAT which increased to 1.93 mm at rice harvest. Similarly, the MWD in lantana-treated plots increased from 0.95-1.75 mm at 7 DAT to 2.73-3.64 mm at rice harvest. The corresponding values of WSA > 0.25 mm dia at 7 DAT and at rice harvest were 33.6 and 62.0 per cent in

control plots, and 42.2-64.2 and 71.5-86.6 per cent in lantana-treated plots, respectively. Bulk density of whole soil (0-0.30 m soil depth), aggregates (2-8 mm dia) and soil clods (4-6 cm dia) determined at rice harvest decreased significantly with lantana treatments. Bulk density in surface layer decreased by 6-19 per cent, in subsurface layer by 2-6 per cent, in soil aggregates by 7-14 per cent and in soil clods by 4-7 per cent over control. The particle density remaining the same, decrease in bulk density was associated with the corresponding increase in total porosity by 9-12 per cent in surface soil layer, 13-27 per cent in soil aggregates and 6-15 per cent in soil clods. The lantana treatments significantly increased the water transmission pores (> 50  $\mu\text{m}$  dia) and decreased the residual pores (< 0.5  $\mu\text{m}$  dia), while did not show much effect on water storage pores (0.5-50  $\mu\text{m}$  dia) when observed at 30 DAT of rice, at rice harvest and at 30 DAS of wheat. The degree of puddling, as assessed through change in apparent specific volume ( $\Delta$  ASV) and puddling index, improved with lantana additions. The  $\Delta$ ASV increased by 67-87 per cent and puddling index by 3-10 per cent over control. The soil penetration resistance (SPR) was determined as a function of moisture content at 30 DAS of wheat at 0.075 and 0.15 m soil depths. The SPR decreased significantly with the amount of lantana additions as well as with moisture content. Lantana additions increased Vertic properties of soil, as was also indicated by increase in COLE values from 0.070  $\text{cm cm}^{-1}$  in control to 0.097-0.116  $\text{cm cm}^{-1}$  in lantana-treated plots. The surface cracking changed from almost hexagonal pattern of wide and deep cracks in control to close network of fine and shallow cracks. Cracking pattern affected clod-size distribution. The tilled surface of control plots had higher per centage of clods > 4 cm dia than in lantana-treated plots.

Lantana additions significantly affected soil hydraulic properties like soil water retention, plant available water capacity (PAWC), saturated hydraulic conductivity ( $K_s$ ), infiltrability, air-filled porosity, and drying pattern of soil. Soil water retention expressed on mass-basis increased at all suction values from saturation to 1500 kPa with lantana addition, but the trend almost reversed on volume-basis; the effects increased with lantana application rate. Correspondingly, the PAWC, while increased on mass-basis, decreased when expressed on volume-basis, during rice season and at rice harvest. However, during wheat season, PAWC increased with lantana, both, on mass- and volume basis. The final infiltrability increased with lantana treatments by 1.5-8 times over control at rice harvest, and 2-4 times at wheat harvest. The increase in  $K_s$  was 1.3-2.1 times over control at rice harvest, and 1.4-4.3 times at wheat harvest. The ten per cent air-filled porosity at 0.075-0.105 m and 0.15-0.18 m soil depth reached earlier in lantana-treated than in control plots after irrigation to wheat at 30 DAS. Also, the surface layer of control plots dried faster than the lantana-treated plots after the rice harvest.

The soil mechanical properties including, soil consistency limits, clod breaking strength (CBS) and energy required to prepare land for wheat sowing showed significant changes due to lantana additions. All the soil consistency limits, viz. liquid limit, plastic limit, shrinkage limit and plasticity index, were higher in lantana-treated than in control plots. Although, the friability moisture range decreased with the lantana from 8.9 to 7.8-8.9 per cent, the moisture content at which soil became friable increased with lantana treatments. The lantana-treated plots required 1.46-1.01 GJ ha<sup>-1</sup> compared with 1.90 GJ ha<sup>-1</sup> energy for preparing land for wheat. It was partly due to reduction in clod breaking strength upon additions. The CBS was significantly, negatively and exponentially correlated with moisture content of clods.

The improvements in soil physical properties were reflected in increased root and shoot growth, and grain and straw yield of, both, rice and wheat crops. A significant interaction between lantana and chemical fertiliser application rates was observed in case of root growth, shoot/root ratio, and grain and straw yields of rice and wheat. Root growth (RMD), in general, increased both with lantana and fertiliser application rates. The RMD of wheat in plots receiving '30Mg lantana ha<sup>-1</sup> + 100 per cent of recommended NK during rice and 66 per cent of recommended NPK during wheat' was the highest in both 0-0.15 m (3.055 kg m<sup>-3</sup>) and 0.15-0.30 m (0.486 kg m<sup>-3</sup>) soil layers. The RMD in control plots was always the lowest in both 0-0.15 m (1.446 kg m<sup>-3</sup>) and 0.15-0.30 m (0.256 kg m<sup>-3</sup>) soil layers. The shoot/root ratio was also the highest (11.9) in plots receiving highest amount of lantana (30 Mg ha<sup>-1</sup>) and chemical fertilisers (100 per cent of recommended NK to rice and 66 per cent of recommended NPK to wheat), and the lowest (7.37) with lowest fertiliser rates (33 per cent of recommended NK to rice and 66 per cent of recommended NPK to wheat) without lantana. Crop yields increased significantly over control with lantana and fertiliser application rates. During 1997, statistically same rice grain yield (2.13 Mg ha<sup>-1</sup>) as in plots receiving 100 per cent NK (without lantana) was observed with '33 per cent NK during rice + 10 Mg ha<sup>-1</sup> lantana' (2.19 Mg ha<sup>-1</sup>) and '33 per cent NK during rice + 20 Mg ha<sup>-1</sup> lantana' (2.33 Mg ha<sup>-1</sup>); with 30 Mg ha<sup>-1</sup> lantana the rice yield even with application of 33 per cent NK during rice was significantly higher (3.48 Mg ha<sup>-1</sup>) than with 100 per cent of recommended NK (without lantana). Wheat grain yields following rice during tenth cropping cycle were statistically similar in plots receiving 33 per cent of recommended NK with 10 (2.02 Mg ha<sup>-1</sup>) and 20 Mg ha<sup>-1</sup> (2.25 Mg ha<sup>-1</sup>) lantana biomass during rice season, but lower than with '33 per cent of recommended NK + 30 Mg ha<sup>-1</sup> lantana

biomass' ( $2.68 \text{ Mg ha}^{-1}$ ). Almost similar trends were observed in case of straw yields of rice and wheat. The total 'rice + wheat' grain yield in plots treated with 33 per cent of recommended NK along with 10, 20 and  $30 \text{ Mg ha}^{-1}$  lantana during rice were 4.21, 4.50 and  $6.16 \text{ Mg ha}^{-1}$  as compared to  $4.18 \text{ Mg ha}^{-1}$  in control plots receiving 100 per cent of recommended NK during rice season (during wheat season all the plots received an uniform dose of 66 per cent of recommended NPK). According to these data, application of as low as  $10 \text{ Mg ha}^{-1}$  lantana biomass over a period of ten years reduced the requirement of chemical fertilisers to one-third to rice and two-third to wheat. With  $30 \text{ Mg ha}^{-1}$  lantana along with 33 per cent of recommended NK to rice and 66 per cent of recommended NPK to wheat produced about 48 per cent higher grain yield of 'rice + wheat' over the yield with recommended fertiliser but without lantana. Our studies have shown that the contribution of improved soil physical properties on improvement in wheat yield was only to the tune of 4-10 per cent of that of contribution by improved chemical properties.

The 'non-limiting water range' (NLWR), a single value soil physical index suggested by Letey (1985), was slightly modified and evaluated under field conditions. The index was found useful in assessing soil physical properties in relation to plant growth. The improvements in soil physical properties due to lantana additions were clearly indicated by NLWR index. The NLWR increased from 4.35 in control to 7.43-15.40 per cent in lantana-treated plots. The NLWR was significantly, linearly and positively correlated with grain yield of wheat.

## CONCLUSIONS

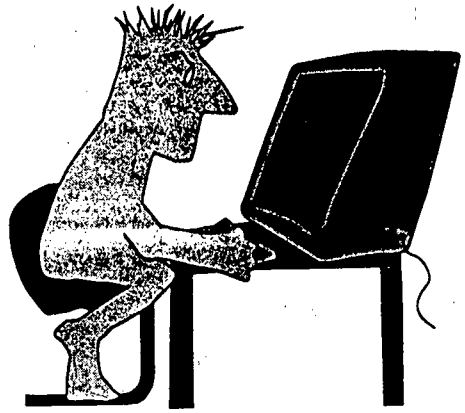
1. The organic carbon in surface soil layer (0-0.15 m) increased from 11.1 (in control) to 12.5-14.6 g kg<sup>-1</sup> and in subsurface (0.15-0.30 m) soil layer from 7.6 to 8.9-10.6 g kg<sup>-1</sup> with the use of lantana @ 10-30 Mg ha<sup>-1</sup> year<sup>-1</sup> over a period of ten years.

2. The addition of lantana for ten years favourably improved all the soil physical properties, viz. soil colour, temperature, aggregation, bulk density, porosity, pore-size distribution, soil penetration resistance, apparent specific volume, puddling index, coefficient of linear extensibility, surface soil cracking behaviour, clod-size distribution, soil water retention, plant-available water capacity, infiltrability, saturated hydraulic conductivity, soil-water contact angle, air-filled porosity, drying pattern of soil, soil consistency limits, clod breaking strength and energy required for land preparation for wheat.

3. The use of lantana along with chemical fertilisers resulted in higher root mass density of wheat in both surface (0-0.15 m) and subsurface (0.15-0.30 m) soil layers as compared to chemical fertilisers alone.

4. The grain and straw yields of both, rice and wheat crop were increased with lantana additions. It was concluded that even with 10 Mg ha<sup>-1</sup> year<sup>-1</sup> lantana over a period of ten years, the doses of chemical fertilisers for rice can be reduced to one-third and for wheat to two-third without affecting crop yields; the use of 30 Mg ha<sup>-1</sup> lantana gave 48 per cent higher grain yield of both 'rice + wheat'.

5. The 'non-limiting water range' (NLWR) a single value soil physical index was found useful in characterising soil physical properties in relation to plant growth. The NLWR increased from 4.35 (in control) to 7.43-15.40 per cent in lantana-treated plots. It was statistically correlated with wheat grain yield.



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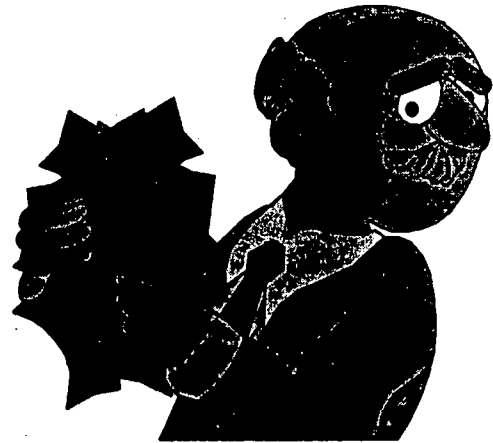
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# APPENDICES

## APPENDICES

### Appendix I

#### Bulk Density Profiles

Treatment (Lantana, Mg ha <sup>-1</sup> )	Bulk density (Mg m <sup>-3</sup> )						
	0-0.03 m	0.03- 0.06 m	0.06- 0.09 m	0.09- 0.12 m	0.12- 0.15 m	0.15- 0.225 m	0.225- 0.30 m
0	1.42	1.43	1.41	1.42	1.41	1.43	1.44
10	1.25	1.36	1.34	1.35	1.37	1.41	1.40
20	1.16	1.24	1.22	1.25	1.29	1.37	1.38
30	0.99	1.13	1.21	1.20	1.20	1.35	1.37
LSD (P=0.05)	0.07	0.06	0.06	0.06	0.05	0.05	0.03

### Appendix II

#### Pore-Size Distribution (%)

Treatment (Lantana, Mg ha <sup>-1</sup> )	Pores (% of total, $\mu$ m)								Total porosity	
	>50	>30	>10	>5	>3	>0.6	>0.5	>0.3		>0.2
<b>During rice season (30 DAT)</b>										
0	24.92	-	35.23	61.89	-	-	65.68	-	67.92	62.27
10	30.01	-	38.51	64.12	-	-	67.94	-	70.40	62.51
20	34.18	-	39.21	63.89	-	-	68.73	-	71.64	63.86
30	33.39	-	43.05	66.64	-	-	70.76	-	73.15	64.06
<b>At rice harvest</b>										
0	5.25	8.76	11.75	14.59	22.16	43.24	44.00	46.99	54.62	51.39
10	6.67	10.98	19.40	22.83	26.46	46.70	48.25	54.01	57.88	53.61
20	10.82	18.57	23.88	27.06	32.93	51.67	52.38	55.28	59.24	55.99
30	12.41	20.69	28.55	33.23	39.04	55.51	56.38	59.84	61.43	57.27
<b>During wheat season (30DAS)</b>										
0	16.95	28.26	36.16	38.23	43.34	56.06	56.14	56.43	60.68	52.44
10	21.92	37.14	45.85	48.59	52.36	63.66	63.07	66.00	68.03	61.18
20	21.55	35.91	46.11	49.36	53.04	63.85	64.28	65.88	68.05	62.54
30	20.16	33.61	45.85	51.88	55.89	65.07	65.47	67.09	69.11	64.32

## Appendix III

## Classification of Soil Pores (Greenland, 1979)

Treatment (Lantana, Mg ha <sup>-1</sup> )	<b>During rice season (30 DAT)</b>			Total porosity (%)
	Pores (% of total, $\mu\text{m}$ )			
	> 50	50-0.05	< 0.05	
0	24.92	40.76	34.25	62.27
10	30.01	37.93	32.06	62.51
20	34.18	34.54	31.28	63.86
30	33.39	37.37	29.24	64.06
		<b>At rice harvest</b>		
0	5.25	38.74	56.01	51.39
10	6.67	41.58	51.75	53.61
20	10.82	41.56	47.62	55.99
30	12.41	44.86	42.73	57.27
		<b>During wheat season (30DAS)</b>		
0	16.95	39.19	43.86	52.44
10	21.92	41.46	36.92	61.18
20	21.35	42.72	35.73	62.54
30	20.16	45.26	34.58	64.32

## Appendix IV

Soil Penetration Resistance (kPa)

Lantana rate (Mg ha <sup>-1</sup> )							
0		10		20		30	
w (%)	SPR	w (%)	SPR	w (%)	SPR	w (%)	SPR
<b>0.075 m soil depth</b>							
35.2	0.68	36.9	0.69	29.7	1.05	30.4	1.40
35.8	0.82	35.6	0.77	30.9	1.00	31.7	0.58
35.9	0.60	33.4	1.13	32.0	0.74	34.5	0.63
35.4	0.43	35.1	0.83	32.5	0.88	31.8	0.88
33.5	0.62	37.9	0.63	33.2	0.78	36.7	0.40
33.9	0.63	36.5	1.04	32.2	0.78	32.4	0.60
34.7	1.28	36.1	0.50	30.6	0.76	32.2	0.66
34.4	0.83	34.8	0.81	29.2	0.91	31.6	1.04
36.6	1.04	31.5	0.89	35.1	0.81	32.0	0.58
30.9	0.76	30.1	0.94	28.9	1.26	30.0	0.68
28.9	1.52	31.2	1.03	28.7	1.23	30.5	0.94
30.5	1.52	30.1	1.04	30.0	0.83	28.8	0.99
31.6	0.89	27.9	1.43	29.4	1.10	26.2	1.00
29.4	1.11	25.4	1.50	27.2	1.08	29.8	1.19
29.5	0.99	30.3	1.27	26.2	1.39	29.2	0.68
30.5	1.29	30.1	1.10	29.5	1.16	30.2	0.91
32.8	1.27	33.8	0.86	30.5	0.83	29.1	0.94
30.9	1.19	30.6	1.07	30	0.94	27.2	1.01
35.0	1.17	27.5	1.24	28.2	1.08	31.4	0.50
29.2	1.11	29.5	1.14	29.4	1.26	29.2	0.99
28.3	1.32	33.8	0.99	28.7	1.21	28.1	0.71
29.4	1.34	36.9	0.59	29.9	1.11	32.2	0.86
26.4	1.32	28.4	1.03	23.9	1.11	31.2	1.19
27.1	1.32	29.5	1.01	25.4	1.20	27.6	1.14
31.6	1.42	30.0	0.73	29.8	1.20	31.2	0.89
26.6	1.09	31.0	1.09	26.6	1.14	29.4	1.17
27.8	1.32	36.0	0.64	29.2	1.04	26.1	1.06
40.4	0.5	38.9	0.4	33.3	0.68	35.7	0.37
40.8	0.45	36.4	0.81	40.4	0.32	37.3	0.40
40.9	0.4	37.7	0.44	39	0.35	36.8	0.37
39.3	0.71	39.6	0.55	32.5	0.67	32.1	0.73
38.1	0.67	38.2	0.6	34.6	0.50	32.7	0.66
38.9	0.53	32.5	0.95	33.2	0.58	36.2	0.57

contd..

<b>0.15 m soil depth</b>							
37.68	1.56	35.6	1.63	33.3	1.45	37.0	1.34
40.65	1.17	36.2	1.37	37.1	1.14	38.8	1.00
42.47	0.95	36.4	1.75	36.4	1.34	34.3	1.44
37.54	0.94	38.2	1.11	37.7	1.04	35.4	0.95
37.38	1.55	39.1	1.25	36.6	1.52	39.9	0.91
38.07	1.30	33.2	1.14	31.9	1.40	29.2	1.36
38.20	1.68	29.5	1.6	35.9	1.14	34.5	1.63
39.05	1.32	33.5	1.23	33.6	1.11	37.7	0.99
33.96	1.29	29.4	1.86	32.7	1.26	31.5	1.12
34.79	1.55	32.2	1.15	35.3	1.27	33.2	1.37
33.81	1.47	31.6	1.53	34.5	1.17	34.9	1.01
35.0	1.42	27.5	1.8	33.8	1.29	33.1	1.37
37.2	1.60	36.4	1.23	34.0	1.63	35.3	1.57
30.9	1.78	32.9	1.32	32.2	1.32	35.6	1.17
34.4	1.68	34.5	1.25	39.5	1.01	34.0	1.42
33.1	1.46	31.8	1.73	32.1	1.34	36.5	1.37
31.8	1.60	31.3	1.83	31.4	1.11	31.3	1.09
34.3	1.40	26.5	1.82	36.3	1.01	28.0	1.57
27.6	1.73	38.3	0.85	31.4	1.42	32.1	1.32
35.0	1.60	37.8	0.95	32.5	1.55	35.4	1.17
30.1	1.52	34.0	1.18	29.2	2.01	34.6	1.32
30.7	1.76	33.4	1.53	29.1	1.91	34.4	1.23
32.8	1.68	27.5	1.78	30.5	2.08	30.9	1.24
34.6	1.88	31.7	1.43	32.4	1.43	32.7	1.40
44.1	0.76	36.9	1.41	41.6	1.06	37.9	0.99
46.0	0.71	39.7	1.08	41.6	0.90	40.7	0.48
44.0	0.69	41.3	0.98	40.6	0.95	44.3	0.68
43.7	0.79	36.9	1.02	41.8	1.00	39.8	1.11
43.2	0.86	41.2	1.04	41.3	0.73	37.8	1.09
43.3	0.85	38.6	0.99	41.2	0.83	44.1	0.76
25.9	2.11	28.5	1.94	26.7	1.58	28.6	1.55
27.5	1.98	30.9	1.59	27.0	1.69	26.3	1.72
28.5	1.88	26.7	2.06	30.5	1.41	25.8	1.68

w = Gravimetric moisture content

SPR = Soil penetration resistance (MPa)

## Appendix V

## Soil-Water Retention (mass-basis)

Lantana Rate (Mg ha <sup>-1</sup> )	Matric Suction (kPa)									
	0	6	10	30	50	100	500	600	1000	1500
	<b><u>During rice season</u></b>									
0	62.27	46.75	-	40.33	-	-	-	21.37	-	19.95
10	62.51	43.75	-	38.44	-	-	-	20.01	-	18.45
20	63.86	42.03	-	38.82	-	-	-	19.97	-	18.11
30	64.06	42.67	-	36.48	-	-	-	18.73	-	17.20
	<b><u>At rice harvest</u></b>									
0	51.39	48.69	46.89	45.35	44.6	41	29.17	28.78	27.24	23.32
10	53.66	50.08	47.72	43.47	41.85	39.41	28.55	27.77	24.63	22.55
20	55.99	49.93	45.89	42.65	41.21	38.54	27.06	26.66	25.04	22.82
30	57.27	50.16	45.42	40.92	38.46	34.91	25.48	24.85	23	22
	<b><u>During wheat season</u></b>									
0	52.44	43.55	37.62	33.48	32.83	29.71	23.04	23	22.85	20.62
10	61.18	47.77	38.83	33.59	32.58	29.67	22.87	22.59	21.46	20.24
20	62.54	49.06	40.08	33.7	32.24	29.37	22.61	22.34	21.31	19.98
30	64.32	51.35	42.7	34.83	31.59	28.37	22.47	22.21	21.17	19.87

## Soil-Water Retention (volume-basis)

Lantana Rate (Mg ha <sup>-1</sup> )	Matric Suction (kPa)									
	0	6	10	30	50	100	500	600	1000	1500
	<b><u>During rice season</u></b>									
0	62.27	46.75	-	40.33	-	-	-	21.37	-	19.95
10	62.51	43.75	-	38.44	-	-	-	20.04	-	18.45
20	63.86	42.03	-	38.82	-	-	-	19.97	-	18.11
30	64.06	42.67	-	36.48	-	-	-	18.73	-	17.20
	<b><u>At rice harvest</u></b>									
0	51.39	48.69	46.89	45.35	44.60	41.00	29.17	28.78	27.24	23.32
10	53.66	50.08	47.72	43.47	41.85	39.41	28.55	27.77	24.63	22.55
20	55.99	49.93	45.89	42.65	41.21	38.55	27.06	26.66	25.04	22.82
30	57.27	50.16	45.42	40.92	38.46	34.91	25.48	24.98	23.00	22.00
	<b><u>During wheat season</u></b>									
0	52.44	43.55	37.62	33.48	32.83	29.71	23.04	23.00	22.85	20.62
10	61.18	47.77	38.83	33.59	32.58	29.67	22.87	22.59	21.46	20.24
20	62.54	49.06	40.08	33.70	32.24	29.37	22.61	22.34	21.31	19.98
30	64.32	51.35	42.70	34.83	31.59	28.37	22.47	22.21	21.17	19.87

## Appendix VI

## Infiltration Characteristics

Lantana rate (Mg ha <sup>-1</sup> )											
0			10			20			30		
CT	i	I	CT	i	I	CT	i	I	CT	i	I
<b>At rice harvest</b>											
5	9.60	2.88	5	14.83	4.45	5	20.56	7.45	5	26.39	10.92
10	2.61	3.67	10	7.28	7.22	10	17.69	12.61	10	20.67	17.12
30	1.36	4.98	15	2.92	10.95	15	13.67	16.76	15	15.14	21.66
40	0.61	5.41	25	3.64	12.13	20	10.58	19.93	20	20.08	27.68
50	0.58	5.94	30	0.47	14.48	25	5.75	20.00	25	15.14	32.22
60	0.47	6.55	40	2.47	15.96	30	4.31	23.04	30	15.14	36.22
70	0.39	6.90	50	1.03	16.58	40	4.72	25.86	35	12.22	40.43
85	0.28	7.16	60	1.03	17.19	45	4.39	27.18	40	11.94	44.01
100	0.86	7.95	70	0.86	18.71	55	3.55	29.72	45	11.64	47.51
130	0.44	8.73	80	0.86	19.23	65	3.39	32.36	50	7.00	49.60
160	0.44	9.52	95	0.78	20.93	75	3.08	34.62	55	5.08	52.91
190	0.33	10.13	110	0.28	21.20	85	2.92	36.97	65	4.36	54.97
220	0.39	10.83	140	0.69	21.35	95	2.68	38.42	75	3.64	56.15
250	0.33	11.44	170	0.44	22.20	115	2.47	39.41	95	3.56	58.43
280	0.39	12.14	200	0.69	22.51	145	2.12	51.15	110	3.11	60.23
310	0.28	12.66	230	0.44	22.80	175	1.72	41.79	125	2.72	61.87
340	0.28	13.16	260	0.44	23.09	205	1.42	42.85	140	2.81	62.20
370	0.28	13.71	290	0.44	23.31	235	1.12	43.73	165	2.26	63.20
380	0.28	14.56	320	0.44	23.66	265	1.15	43.41	195	2.26	64.01
						3.25	1.12	43.66	225	2.22	64.79
									255	2.22	64.79
									285	2.22	66.35
									345	2.22	67.11

contd...

<b>At wheat harvest</b>											
5	42.4	3.20	5	105.9	7.99	5	209.6	15.04	5	291.9	20.48
10	38.0	6.07	10	101.6	15.65	10	170.7	28.09	10	264.2	39.01
15	36.1	8.79	15	96.1	22.90	15	167.5	41.89	15	251.1	56.63
20	35.1	11.43	20	92.3	29.80	20	160.0	53.89	20	227.3	72.58
25	33.8	13.98	25	82.1	35.99	25	157.5	68.86	25	205.3	86.98
35	33.2	15.23	35	80.0	39.01	30	155.6	79.86	30	188.4	100.20
45	32.2	16.44	45	79.8	42.02	35	151.2	92.32	35	175.8	112.53
55	30.3	17.58	55	67.4	44.56	40	146.2	103.38	40	167.4	124.23
65	27.9	18.63	65	64.9	47.04	45	141.1	115.03	45	164.8	135.79
75	27.7	19.67	75	56.9	49.22	50	137.4	125.05	50	152.6	146.49
85	26.5	20.67	85	54.2	51.26	55	136.1	136.61	55	150.7	157.06
95	25.2	21.62	95	52.8	53.25	60	131.1	147.44	60	145.0	167.23
110	24.1	22.23	110	50.9	54.53	65	129.8	158.17	70	142.5	174.23
125	22.5	22.8	125	14.8	55.74	75	126.1	160.4	80	135.1	178.97
140	21.8	23.35	140	44.8	56.87	85	123.6	169.59	90	125.6	183.37
155	20.7	23.87	155	44.4	57.99	95	115.1	174.70	100	124.2	185.73
170	19.8	24.37	170	43.7	59.09	105	105.7	179.50	110	117.6	191.86
185	19.2	24.85	200	41.5	29.61	115	105.4	184.88	120	107.4	195.63
215	17.8	25.07	230	38.9	60.10	125	103.2	188.25	135	100.3	197.30
245	17.2	25.28	260	34.9	60.54	140	101.9	193.10	150	97.8	200.30
275	16.1	25.48	290	29.5	60.91	155	99.5	196.92	165	89.3	202.39
305	15.3	25.67	320	25.4	61.23	170	88.9	198.67	180	78.9	204.39
335	14.5	28.85	350	23.8	61.53	200	87.5	201.94	210	77.9	205.30
365	13.9	26.02	380	20.6	61.79	230	73.8	202.06	240	69.2	206.11
395	13.0	26.18	410	18.1	62.02	260	67.3	204.09	270	60.3	207.11
425	12.4	26.34	440	17.8	62.24	290	62.3	205.03	300	51.1	208.42
455	9.70	26.42	470	17.2	62.46	320	56.7	206.00	330	48.1	209.18
485	9.1	26.57	500	17.2	62.68	350	52.1	206.69	360	46.5	209.51
515	8.7	26.68	530	17.38	62.90	380	49.4	207.43	390	42.9	210.01
545	8.7	26.79	560	17.2	63.12	410	44.4	208.13	420	40.6	210.48
575	8.7	26.90	590	17.2	63.34	440	40.6	209.13	450	38.8	210.93
605	8.7	27.01				470	36.9	209.34	480	35.7	211.35
						500	35.1	210.34	510	35.8	211.77
						530	29.9	210.87	540	35.5	212.18
						560	28.1	211.35	570	35.5	212.59
						590	27.8	211.78	600	35.5	213.00
						620	27.6	212.17	630	35.5	213.41

CT = Cumulative time (min)

i = Infiltration rate ( $\times 10^{-6}$  m s<sup>-1</sup>)

I = Cumulative infiltration (mm)

## Appendix VII

Air-Filled Porosity ( $f_a$ , %)

Days after irrigation	$\theta$ (%)	$f_a$	$\theta$ (%)	$f_a$	$\theta$ (%)	$f_a$	$\theta$ (%)	$f_a$
<b>0.075-0.105 m soil depth</b>								
1	40.85	7.53	39.60	10.40	40.00	14.50	38.10	17.64
2	39.85	8.53	38.90	11.10	39.00	15.50	37.80	17.94
4	38.50	9.88	38.10	11.90	37.90	16.60	36.70	19.04
5	36.60	11.78	37.30	12.70	35.10	19.40	36.00	19.74
7	35.70	12.68	36.60	13.40	34.60	19.90	34.50	21.24
9	34.83	13.55	35.90	14.10	33.20	21.30	32.50	23.44
12	33.40	14.98	34.50	15.50	32.30	22.21	31.80	23.94
15	31.00	17.38	31.60	18.40	30.40	24.11	30.90	24.84
18	29.40	18.98	30.30	19.70	29.60	24.61	30.00	25.74
20	28.60	19.78	30.10	19.90	29.00	25.51	29.30	26.44
22	27.50	20.88	29.10	20.90	28.20	26.31	28.70	27.04
24	26.50	21.88	27.70	22.30	25.50	29.01	27.40	28.34
<b>0.15-0.18 m soil depth</b>								
1	45.99	0.00	41.34	0.87	41.83	2.02	40.70	3.97
2	44.09	0.00	40.40	1.81	40.62	3.23	39.84	4.83
4	43.40	0.00	38.67	3.54	39.46	4.39	39.31	5.36
5	42.50	0.00	38.21	4.00	37.40	6.45	37.85	6.82
7	40.70	0.69	37.00	5.21	36.40	7.45	36.83	7.74
9	38.60	2.79	35.28	6.93	35.23	8.62	35.39	9.28
12	37.90	3.49	33.42	8.79	33.67	10.18	34.60	10.07
15	36.90	4.49	32.58	9.63	32.37	11.48	34.10	10.57
18	34.60	6.79	31.58	10.63	31.56	12.29	32.98	11.69
20	33.80	7.59	29.94	12.27	30.53	13.32	31.44	13.23
22	31.53	9.86	28.00	14.21	29.17	14.68	28.58	16.09
24	27.40	13.99	26.91	15.3	26.83	17.02	26.03	18.64

$\theta$  = Volumetric moisture content

## Appendix VIII

Drying pattern of soil at rice harvest

DAT	Matric suction (kPa)							
	0.15 m depth				0.30 m depth			
89	1.29	1.04	0.92	0.66	0.55	-	-	-
90	2.43	2.3	2.05	1.8	0.55	-	-	-
91	3.56	3.43	3.18	2.93	1.40	0.93	0.80	0.55
92	4.95	4.82	4.57	4.57	2.94	2.56	2.31	2.06
93	6.84	6.21	5.95	5.32	4.33	4.20	3.95	3.45
94	8.47	8.22	7.85	7.42	5.97	5.59	4.96	4.58
95	9.73	9.23	8.73	8.6	7.23	6.60	5.84	5.59
96	11.23	10.87	10.62	10.11	8.73	8.36	8.11	7.86
97	12.88	12.38	12.13	11.88	10.25	9.62	9.37	8.49
98	13.51	13.26	12.51	12.25	11.38	10.88	10.5	10.12
99	14.52	14.14	13.51	12.75	12.14	12.14	11.84	11.38
100	16.41	15.91	15.78	14.77	14.41	13.78	13.64	12.90
101	18.18	17.55	17.17	16.92	15.50	15.29	15.16	14.66
102	20.95	19.44	19.06	18.3	18.31	17.05	15.79	15.16
103	22.33	21.58	20.44	20.02	19.20	18.31	17.94	17.13
104	23.47	22.46	21.96	21.2	20.18	19.70	19.20	18.94
105	24.22	23.72	23.56	23.22	21.92	20.96	20.71	19.70
106	23.72	23.34	22.96	22.46	21.84	20.83	20.58	19.45
107	26.24	25.48	24.98	24.73	24.49	22.22	21.46	20.96
108	29.14	28.13	27.25	26.74	25.87	24.61	23.48	22.22
109	38.41	34.05	33.67	32.16	30.79	29.53	28.52	27.13
110	38.46	36.82	36.32	35.82	34.44	33.18	32.30	31.92
111	43.63	41.36	40.75	38.84	39.61	37.34	36.08	35.58
112	47.79	46.27	44.38	43.75	43.51	40.99	39.96	39.23
113	51.44	49.93	48.42	46.4	46.54	45.40	44.94	43.26
114	54.84	52.2	50.05	48.79	50.95	48.43	46.16	45.66
115	60.26	57.87	55.6	54.97	58.63	56.25	50.95	48.18
116	67.82	66.18	59.38	58.87	63.55	57.88	55.36	51.07
117	71.47	64.92	63.16	62.65	66.70	65.44	58.63	55.86
118	74.5	71.98	71.35	68.83	68.71	66.32	61.12	58.38
119	75.14	73	71.36	70.86	69.72	67.96	63.55	62.04

DAT = Days after transplanting

## Appendix IX

Clod breaking strength (CBS, kPa)

Lantana Rate (Mg ha <sup>-1</sup> )							
0		10		20		30	
w (%)	CBS	w (%)	CBS	w (%)	CBS	w (%)	CBS
11.12	589.9	10.62	472.9	10.28	338.9	11.58	283.6
13.22	475.1	12.23	353.8	12.40	316.9	13.33	261.6
15.76	355.9	15.49	274.3	14.90	248.8	14.96	224.9
16.50	236.8	16.41	197.3	16.85	199.0	15.25	204.0
17.27	193.7	17.48	177.3	17.81	173.5	17.19	168.9
18.46	176.0	18.25	132.5	18.27	124.5	18.47	115.5
19.47	158.0	19.99	126.1	19.48	109.5	19.65	106.6
20.76	135.1	20.37	119.7	20.21	97.1	20.57	97.8
21.60	116.6	21.60	113.4	21.48	80.2	22.41	87.4
22.26	94.3	22.00	87.8	22.50	75.1	23.55	61.9
23.50	76.7	23.88	69.5	23.81	68.1	24.40	57.9
25.61	59.5	25.58	49.5	25.57	35.1	25.76	30.4

w = Moisture content

## Appendix X

Non-Limiting Water Range

Moisture content (%) at		Non-limiting water range (%)	Wheat grain yield (Mg ha <sup>-1</sup> )
10 % air-filled porosity	2 MPa SPR		
31.21	26.81	4.40	2.20
31.21	27.11	4.10	2.05
31.21	26.66	4.55	2.00
32.22	23.89	8.33	2.25
32.22	24.90	7.32	2.35
32.22	25.58	6.64	2.50
33.85	24.23	10.72	2.10
33.85	22.80	11.05	2.68
33.85	22.95	10.90	2.50
34.67	19.48	15.19	2.85
34.67	20.60	14.04	2.75
34.67	18.81	15.85	3.08

SPR = Soil penetration resistance (MPa)