PROFILE WATER EXTRACTION THROUGH WATER–NITROGEN–TILLAGE INTERACTION IN WHEAT

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
(SOIL SCIENCE)

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Dedicated to the Sweet Memory of Our Beloved

Sub/Lieutenant Vinod Kumar Sharma
(Indian Navy)

Who left us for heavenly abode on 24th June 1991 at the Age of 27, and Could not Cherish his dream of Operational Research

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CERTIFICATE - I

This is to certify that the thesis entitled "Profile water extraction through water-nitrogen-tillage interaction in wheat", submitted for the degree of DOCTOR OF PHILOSOPHY (AGRICULTURE) in the subject of Soil Science of Himachal Pradesh Krishi Vishvavidyalaya, Palampur, is the bonafide research work carried out by Shri Jagjeet Chand Sharma son of Shri Ishwar Dass Sharma under my supervision and that no part of this thesis has been submitted for any other degree.

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

CL Acharya
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Dated: 24.01.1992

CERTIFICATE - II

This is to certify that the thesis entitled "Profile water extraction through water-nitrogen-tillage interaction in wheat", submitted by Shri Jagjeet Chand Sharma son of Shri Ishwar Dass Sharma to the Himachal Pradesh Krishi Vishvavidyalaya, Palampur, in partial fulfilment of the requirements for the degree of DOCTOR OF PHILOSOPHY(AGRICULTURE) in the subject of Soil Science has been approved by student's Advisory Committee after an oral examination of the same in collaboration with an external examiner.

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Errors and omissions are mine.

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CONTENTS

LIST OF SYMBOLS

a	empirical constant
A	cross sectional area of soil (cm^2)
AH	at harvest
b	empirical constant
^oC	drgree celsius
CD	critical difference
cm	centimetre
CRI	crown root initiation
CSDD	cumulative stress drgree days (^oC)
DAS	days after sowing
FS	flowering stage
g	gram
h	matric potential (-mbar); time (hour)
H	hydraulic potential (-mbar)
K	hydraulic conductivity ($cm\ d^{-1}$)
K_s	saturated hydraulic conductivity ($cm\ d^{-1}$)
LAI	leaf area index
LDR	leaf diffusion resistance ($s\ cm^{-1}$)
m	metre
mm	millimetre
Mg	megagram
MT	maximum tillering
MWD	mean weight diameter (mm)
n	empirical constant
NS	non-significant
Q	steady state volume of outflow (cm^{-3})
r_z	water uptake by roots (cm^3 of water cm^{-3} of soil d^{-1}or d^{-1})
R_z	total water extraction by roots ($cm\ d^{-1}$)
RLD	root length density (m^3m^{-3})
RLWC	relative leaf water content (%)
RMD	root mass density ($mg\ m^{-3}$)
SA	stable aggregates
SDD	stress degree days (^oC)
SMS	soil moisture storage (cm)
SWP	soil water potential (-mbar)
S_z	profile water depletion (cm) upto depth Z

t(d, h, s)	time (days, hour, second)
T	temperature (^{o}C)
Ta	air temperature (^{o}C)
Tc	crop canopy temperature (^{o}C)
V_z	soil water flux (cm d^{-1})
W	total water content (cm)
XWP	xylem water potential (-bar)
Z	depth (cm); gravitational head (cm)
θ	volumetric water content ($cm^3 cm^{-3}$)
Ψ	matric potential; matric suction (mbar)
$\sum$	sigma (summation)
%	per cent

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INTRODUCTION

INTRODUCTION

Wheat (Triticum aestivum Linn. emend. Fiori and Paol.) is the major cereal crop of winter season and forms a staple food of the habitants of Northern India. In India, the crop is grown in 24.09 million hectares with annual foodgrain production of 53.99 million tonnes (Anonymous, 1990). The corresponding figures for Himachal Pradesh are 373.20 thousand hectares and 51.32 thousand tonnes (Anonymous, 1990). The figures for average yield of the crop for India and Himachal Pradesh are 22.41 and 13.60 q ha^{-1}, respectively, which are much lower than those of major wheat producing countries such as U.S.A., U.K., Argentina and Australia.

From acreage point of view wheat ranks first among all the cereal crops in Himachal Pradesh, but the average yield in the state is much lower than the national average. This is inspite of the fact that more than 90 per cent of the wheat growing area in the state is under high yielding varieties. The main reasons for low yield are (i) the large area under rainfed conditions, (ii) low input of nutrients, (iii) poor soil and water management practices, (iv) occurrence of sub-optimal air temperatures, and (v) less weed control and plant protection measures. Only 17 per cent of the total area under wheat is having assured irrigation. Practically in all major wheat growing areas of the state, about 80 per cent of annual rains are received from mid June to mid September. Winter rains are meagre, erratic and quite often wheat crop suffers from moisture stress. In the absence of timely rain and pre-sowing irrigation facility, the sowing of the crop is considerably delayed resulting in poor yield.

At recede of monsoon rains, the soil profile is wet which soon starts losing moisture after harvest of maize. The seed-zone gets desiccated by the time wheat is to be seeded. The lower layers, however, continue to remain wet and contribute very little moisture for wheat growth due to poor water transmission characteristics (Chenkual and Acharya, 1990). Even a small fraction of moisture stored in the seed-zone has a favourable effect on germination and early establishment of the wheat crop (Acharya and Kapur, 1988). The subsurface depths, in general, are compact and restrict root growth (Bhagat and Acharya, 1987). The moisture in these depths thus remains untapped.

The different tillage operations are known to modify the water use by crops through their effect on profile water storage and its utilization (Bennie and Goss, 1986).Deep tillage enhances water intake and its storage and provides favourable environment for root growth in subsurface depths (Acharya and Bhagat, 1984; Bhagat and Acharya, 1987; Barbosa et al., 1989). In situations like ours in the state where land is mostly slopy and undulating, tillage not only provides greater opportunity for infiltration and retention of rain water, but also reduces soil erosion owing to reduced runoff. Early tillage after harvest of the previous crop, thus, may irrigation facility, the sowing of the crop is considerably delayed resulting in poor yield.

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The water depletion from deeper depths is a function of atmospheric demand, soil water storage and its transmissibility, rate of root extension, rooting density and frequency of rains or irrigation. Under the situations where root length and proliferation are restricted, the roots can be made to penetrate deeper with deep tillage. However, water may be a limiting factor for enhancing root growth if subsurface depths are deficient in moisture storage for optimum root growth.

A strong interaction exists between nitrogen application and moisture supplies in the soil profile. The response of N application varies with the soil texture (Singh _et al._, 1975) and until a critical threshold moisture content is reached, there is no response of N application (Prihar _et al._, 1985). Higher levels of N result in greater root growth (Jat _et al._, 1976b) that keep the canopy of wheat cooler and hence less stressed than that of N deficient crop (Seligman _et al._, 1983). Nitrogen fertility influences plant water relations (Shimshi, 1970; Radin and Parker, 1979; Radin and Boyer, 1982; Upreti and Sirohi, 1986). Thus, the nitrogen supply at appropriate quantity and at the desired depth plays an important role for early establishment of roots which may go deeper and extract water from these depths. This, however, is governed by the water content at the shallower depths. For each amount of N supply

there has to be a critical moisture content in the soil below which the desired response of applied N is not obtained. Thus, the plant and root growth is affected by soil-water content and N levels, whereas, the moisture supplies within the soil profile are governed, to a large extent, by the manipulations done at the surface and subsurface depths (Bhagat and Acharya, 1988).

Different indices have been proposed by several workers (Weatherley, 1950; Waring and Cleary, 1967; Idso et al., 1977) to identify the moisture stress experienced by the crop. Certain stages have been identified that are comparatively more sensitive than others to moisture stress. These indices are based on both amount and energy status of water in the soil and plant. Since soil-plant-atmosphere is one continuum, the water production function evaluated in one system must correlate well with the other, determined in the other system for identifying moisture stress in the crop. However, there are limitations of measurement within each component of this continuum. The levels of soil management, nitrogen application, and water supplies in the soil profile which govern plant and root growth are likely to influence profile water extraction and various water production functions. Profile water extraction, therefore, is a complex phenomenon dependent on soil moisture storage and its availability, nitrogen supply and structural status for root proliferation. The information on these interaction aspects is lacking, although, there are some studies to relate plant and root growth and water extraction patterns, individually with such factors as water supplies, nitrogen levels, and tillage depths. The studies, were, therefore, undertaken with the following broad objectives:

1- To evaluate the water extraction pattern from different depths by wheat crop as a function of soil water stocks, nitrogen levels and tillage depths;

2- to evaluate the plant and root growth parameters in wheat as influenced by soil water stocks, nitrogen levels and tillage depths;

3- to evaluate the water stress in wheat crop as related to root growth and development in the surface and subsurface depths; and

4- to correlate the different water production functions such as leaf water status, day degree stress and crop canopy temperature with profile water status.

REVIEW OF LITERATURE

REVIEW OF LITERATURE

In this chapter, literature pertaining to the effect of soil moisture regimes, nitrogen levels and tillage depths on water use and its depletion pattern, plant and root growth parameters, various plant water stress indices and their relation with profile water storage, soil water suction, has been briefly reviewed under the following heads:

2.1 Effect of tillage

2.1.1 Effect of tillage on soil physical properties and plant growth

2.1.2 Effect of tillage on water uptake from soil profile

2.2 Effect of moisture regimes

2.2.1 Effect of moisture regimes on root and plant growth

2.2.2 Effect of moisture regimes on water uptake from the soil profile

2.3 Effect of nitrogen

2.3.1 Effect of nitrogen on root and plant growth

2.3.2 Effect of nitrogen on water uptake from soil profile

2.4 Interaction effect of moisture, tillage and nitrogen on root and plant growth and water uptake from the soil

2.5 Water production functions (stress indices) in relation to soil moisture regimes, nitrogen and tillage depth

2.6 Inter-relationships between various water production functions

2.1 Effect of Tillage

Tillage refers to the mechanical manipulation of soil to obtain seed bed physically, chemically and biologically suited to crop plant. Soil tillage methods such as conventional and deep tillage are considered important soil management practices for a successful wheat crop, which alter the soil physical environment and affect the plant and root growth, water and nutrient uptake and crop yield.

2.1.1 Effect of Tillage on Soil Physical Properties and Plant growth

Tilling or ploughing over years produces a plough pan at a certain depth, which is a characteristic of the average depth of ploughing over years. Yet another possibility of occurrence of a hard limiting pan at the subsurface layer can be continued field traffic (Moorman and Van Breeman, 1978) or clay migration from the surface layer, particularly under rice culture (Mottomura et al., 1970). These limiting layers besides impeding water movement in soil also restrict the elongation and proliferation of roots. Attempts have been made over years to shatter these hard pans by deep ploughing the land to provide a better environment for plant growth. There has been large variations in the success of deep ploughing operations. This would depend upon type of soil, the nature of crop, the climate and economics of the operation. Burnett and Tackett (1968) indicated that deep ploughing modifies the soil physically and results in greater utilization of subsoil moisture.

Numerous experiments reported the beneficial effects of deep ploughing. Increased yields of corn and cotton have resulted from deep tillage and placement of fertilizers in soils where root penetration was restricted by a traffic pan (Pattric et al., 1959). Also there has been increased utilization of subsoil moisture during drying periods between rains by the deep root system. Favourable effect of deep ploughing on the modification of soil hydraulic properties, viz., infiltration and permeability has also been observed. Yumura and Ishihara (1971) indicated that drainage of poorly drained heavy Ultisols increased with deep ploughing and contributed towards the increased yields of teosinte and corn to the tune of about 10 per cent over conventional ploughing. Acharya and Bhagat (1984) also reported higher infiltration under deep ploughing which favourably moderated the air-water relations through quick disposal of heavy storms during maize growth and produced higher grain yield. Bhagat and Acharya (1987) reported that deep ploughing encouraged greater upward flux during the dry period of wheat growth. This coupled with higher rooting density under this treatment resulted in increased grain yield of wheat.

Allamaras et al. (1977) reported that in a layered silt loam, hydraulic conductivity increased after deep ploughing, however, the effect was more pronounced in the upper 30 cm layer than below, because a layer with low hydraulic conductivity existed between 30-45 cm. Jassen (1979) studied some physical and chemical characteristics of deep ploughed soil upto 70 cm. He observed that organic matter content increased by 20 per cent upto 50 cm depth followed by an improvement in soil structure.

Subharami and Dakshinamurti (1971) studied the effect of various tillage operations on root growth of wheat and maize and revealed that the parameters of root growth like total root length, root diameter, dry weight of roots, root volume, number of primary and secondary roots, etc. were significantly higher with deep ploughing followed by mould board ploughing. Root penetration was better because of improvement in soil structure in the rhizosphere. Allamaras and Nelson (1971) reported that corn root weight configurations were changed by tillage and straw mulch treatments. But the same treatments produced different root growth in two years of study.

Unger (1979) reported significantly higher yields of sugarbeet roots under deep tillage (40cm depth) than with conventional tillage. He attributed this to the improved soil physical conditions resulting from disrupting the dense high strength soil horizon. Increase in root growth under deep ploughing has been observed by Reddy et al. (1977). Bhagat and Acharya (1987) studied the effect of various soil management practices on root growth parameters in wheat and found that the total root length and root density under conventional cultivation + mulch was double to that obtained under conventional cultivation. The mulch treatment was followed by deep ploughing.

In tilled soil a ploughsole layer at 20-30 cm depth induced higher rooting density, but restricted proliferation of roots in deeper layers. The water uptake on oat was functionally related to rooting density and soil water potential (Ehrler et al., 1980). The grain yield of wheat was nearly 20 per cent greater under deep ploughing than in those crops sown by direct drilling. The ploughed treatment had lower soil strength and coincided with more rapid wetting of the subsoil and fast root extension rates (Hamblin et al., 1982).

A study by Bennie and Botha (1986) on the effect of deep tillage and controlled traffic on root growth of maize and wheat showed that deep ripping and controlled traffic lead to a significant increase in rooting depth, rooting density in the subsoil as compared to other tillage treatments. Barbosa et al. (1989) worked on the effect of deep tillage treatments on soil properties, growth and yield of soya in a compacted Ustochrept and revealed that loosening of the compacted layer by deep tillage treatments resulted in lower penetrometer resistance and bulk density and deeper rooting (31 to 33 cm) compared with conventional treatments (24 cm). Deep tilled soya exhibited higher growth rates than conventionally tilled. Increased root growth rates from deep tillage were attributed to deep root penetration which had greater access to subsoil moisture and nutrients, especially during dry periods after emergence.

Sharma (1985) reported that forage accumulation, plant height and final forage yield of fodder oats were significantly less under minimum tillage (T_1) than under reduced tillage (T_2)

or conventional tillage (T_3). Reduction in yield under T_1 was associated with restricted root growth and high soil strength and bulk density in the surface and subsurface layers. Majid et al. (1987) studied the effect of different tillage techniques on wheat production and recorded maximum grain yield of 5.5 t ha^{-1} with deep ploughing which was a 28 per cent increase over conventional cultivation. Increase in yield was attributed to better root development, utilization of soil moisture and redistribution of nutrients.

Sharma and Acharya (1987) studied the effect of soil management on plant growth and yield of rainfed wheat and recorded significantly higher dry matter yield in deep ploughing than conventional cultivation at stem elongation and heading stages of wheat growth during 1981-82 and at heading during 1980-81. Deep ploughing gave significantly higher grain yield over conventional cultivation during both the years of study. The study further revealed that increased plant growth and yield under these tillage practices was a consequence of better soil physical environment that enhanced gross root weight and its activity and in turn shoot growth.

Orellana et al. (1990) noted significantly higher yield of soya with deep tillage treatment compared to conventional tillage. They attributed the higher yield to improved drainage associated with lower penetrometer resistance during the exceptionally wet germination emergence period. Arora et al. (1991) studied the tillage effects on corn in sandy soils in relation to water retentivity and water management and seasonal evaporativity and found that increasing tillage depth from 10 to 30 cm increased the mean yield from 2.8 to 4.7 t ha^{-1} in the unmanured plots and 3.8 to 5.4 t ha^{-1} in the manured plots. Gajri et al. (1991) also studied the tillage effects on yield of wheat crop on coarse textured soils and found that deep tillage significantly increased grain yield over conventional tillage and on an average it was 12.0 per cent higher with deep tillage.

2.1.2 Effect of Tillage on Water Uptake from Soil Profile

Tillage helps in controlling weeds, improvement in soil physical properties, conservation of moisture, free exchange of gases in soil and air which results in better root growth, their penetration to subsurface depth and hence greater utilization of subsoil moisture (Burnett and Tackett, 1968; Allamaras et al., 1977; Hamblin et al., 1982; Bhadoria, 1988; Orellana et al., 1990). Increase in moisture uptake (Czeratszki and Shulze, 1971; Carlson, 1978; Unger, 1979) and root growth followed by grain yield (Reddy et al., 1977; Trouse, 1979) have been observed through deep ploughing.

Bhagat and Acharya (1988) studied the water uptake (r_z) by wheat roots under various management practices and showed that the treatment having deep tillage maintained higher uptake values from the subsurface depths. The total water withdrawal from the profile 'R_z' (integral of r_z from 0 to 60 cm depth) was the highest (1.183 cm d^{-1}) under this treatment and the lowest (0.5738 cm d^{-1}) under the treatment having zero cultivation. Similarly, Sood (1987) also studied the water uptake by potato roots after rice crop from different depths under various treatments. When deep puddling, compared to conventional puddling was imposed before planting of rice, its effect prevailed in the subsequent crop of potato too. This treatment extracted greater amount of water in potato in comparison to the remaining treatments.

2.2 Effect of Moisture Regimes

Soil moisture is one of the most important factors which govern the crop stand and ultimately its yield. In the absence of optimum moisture, seed does not germinate. Water is essential for absorption and conveyance of various mineral nutrients from soil as well as for the various physiological processes like photosynthesis and transpiration.

2.2.1 Effect of Moisture Regimes on Root and Plant Growth

Well developed root system invariably produces higher yields. Restricted root growth results in reduced nutrient and water uptake and poor growth of plants (Drew, 1978; Peterson *et al*., 1984). Root growth may be affected as a result of inadequate moisture in the soil, mechanical impedance (Taylor and Gardner, 1963; Taylor and Ratliff, 1969; Chaudhary and Sandhu, 1983) and suboptimal thermal regime (Acharya and Bhagat, 1984).

A dense network of roots in wheat developed when soil moisture tension was above 15 atmosphere and under favourable moisture conditions roots were observed to a depth of 13 feet (Kmoch et al., 1957). Extent of root growth of cereal plant was highly correlated with the soil moisture level (Salim et al., 1965). A nonlinear decrease in root elongation of wheat and mung was noted as the soil moisture stress increased from -0.3 to -1.5 bar (Gupta and Singh, 1975). Oat plants growing under soil moisture stress showed rooting to a greater depth (Sandhu and Horton, 1977). The root growth of wheat at heading was linearly related to the soil water content in the surface 30 cm of the soil during the 30 to 60 days period (Gajri and Prihar, 1985). Ehrler et al. (1980) showed that the relative growth rate of root length decreased with soil water potential and ended at -19 bar.

Bhatia et al. (1977) studied the rooting pattern of wheat in relation to soil moisture regime and revealed that rooting depth increased from 60 cm with 7.5 cm soil moisture to 90 cm with 25 cm soil moisture in the upper one metre of soil profile, but found no significant differences in the root weight or rooting depth between 20 and 25 cm treatments. Mehta et al. (1985) studied the rooting pattern of different genotypes of wheat in relation to irrigation and found that root weight and grain yield increased with increasing number of irrigations. Ahmed and Misra (1986) reported curvilinear decrease in root length density of wheat grown under rainfed or with 1 to 4 irrigations.

Soil moisture stress effects almost every aspect of plant growth and development by modifying the morphological, physiological and chemical characteristics of a plant. Plant growth is an integrated effect of many factors any of which may restrict the growth. The adverse effect of soil water deficit on crop growth and yield is well documented (Aspinall*et al.*, 1964; Hsiao, 1973). Many research workers have reported that plants under continuous readily available soil moisture conditions during growing period make more total growth than the plants under limited water supply (Goode and Hyrycz, 1964; Fieldstein and Childers, 1965; Carlson, 1967; Frendrich, 1967; Goode and Ingram, 1972; Janjic *et al.*, 1972; Cripps, 1981).

Day and Intalap (1970) demonstrated that water stress in wheat at jointing stage not only reduced the number of days to flower, but also resulted in shorter plants, more lodging, lower grain yield and fewer seeds per head. Carbon (1971) noted that increased diurnal water stress reduced plant growth and tiller numbers in grain sorghum. Also, less water was evaporated from the treatment showing the greatest levels of diurnal water stress.

Patil and Batkal (1975) recorded the highest grain yield in wheat when irrigations were scheduled at tillering, boot leaf, flowering and grain development stages. An increase in number of irrigations increased the effective tiller number per metre row length, grain number per ear, grain weight per ear and 100 grain weight which culminated in the increased yield of wheat. Sandhu and Horton (1977) timed the water stress period in oats to occur during the boot leaf stage and the anthesis through early grain formation stage (separately and in combination) and noted that stress at either stage decreased plant height and number of florets per panicle. Water stress at all stages caused a marked decline in the yield of straw, top without panicle, kernels and dehulled kernels. Stress at boot leaf stage and at anthesis through early grain formation reduced yield 20 and 85 per cent, respectively whereas combined stress reduced kernel yield by 67 per cent.

Ritchie (1976) summarised the effects of soil water deficits on plant growth and reported that during vegetative growth a decrease in soil water availability was first reflected in decreased expansive growth without any decrease in photosynthesis and transpiration. This reduced the sink size of active leaves for the storage of photosynthates which were then preferentially transported to roots and root growth was stimulated at the expense of shoot growth. A study by Upreti and Sirohi (1985) on the effect of water stress on leaf area development and grain yield of two wheat varieties (Kalyansona and C-306) showed that water stress treatment had brought significant reduction in specific leaf area (cm^2g^{-1}) in both the varieties. Water stress at tillering, anthesis and seed development stages significantly reduced the grain yield of 'Kalyansona', whereas in 'C-306' reduction was observed due to stress at anthesis and seed development stages only. Stress treatment brought significant decrease in leaf area development in both the varieties.

Gogoi (1983) reported significant increase in leaf area index (LAI) with each additional irrigation at different physiological growth stages of wheat crop. Hochman (1982) found that stress from tillering to anthesis stage in wheat reduced LAI and grain number and decreased grain yield by 28 per cent compared with control. Stress from boot leaf to grain filling stage gave reduced grain number and grain weight and caused 36 per cent reduction in grain yield. Stress during grain filling stage reduced 100 grain weight and grain yield was 16 per cent below that of the control. Jalota <u>et al</u>. (1985) showed that wheat is more sensitive to stress from flowering to grain formation stage.

Singh and Malik (1983) studied the effect of water stress at three growth stages of wheat and found that a maximum yield of 5.2 t ha^{-1} was recorded with no water stress treatment. All levels of water stress except -0.5MPa during flowering to maturity reduced grain yield significantly compared with no stress treatment. The greatest effect of water stress on grain yield was observed during sowing to jointing stages when the highest reduction in grain yield (33.5%) was with -1.5 MPa water stress. Similar water stress during jointing to flowering and flowering to maturity reduced grain yield by 26 and 22.6 per cent, respectively. Sharma et al. (1981) found that weekly percentage increase in green matter production of wheat was greatest at field capacity (-0.3bar) and decreased sharply as stress increased to -5.0bar and thereafter linearly reaching negligible value at -17bar. Leaf area, stem height, relative to those of unstressed plant decreased sharply to -5.0bar and slowly thereafter. Shoot:root showed similar trend. Hassan (1987) recorded less number of tillers per square metre and leaf area in wheat under moisture stress.

2.2.2 Effect of Moisture Regimes on Water Uptake from Soil Profile

The rate of water uptake by plants from a given volume of soil depends on rooting density, water retention and transmission characteristics of the soil as well as on the potential gradient at the soil root interface (Gardner, 1964). The water uptake is highest where rooting density is greatest provided that the matric suction is uniform throughout all depths of the rooting zone. Normally, there are differences in the rooting density within the soil profile which results in the non uniformity of water uptake from the depths of rooting zone (Ogata et al., 1960).

Gajri and Prihar (1985) showed that the capacity of plant to absorb water with limited supply was closely related to the size of the root system, root weight index (RWI = mg root cm^{-3} soil surface in the entire rooting zone) and available soil water fraction (ASWF) as both influence water uptake by the crop. With high RWI a higher rate of water uptake could be sustained even at relatively low ASWF. Higher leaf water potential at higher RWI irrespective of ASWF also showed the over-riding importance of the root system for water uptake by the crop. Inter-relations among root growth, water use and grain yield are ascribed to positive effects of rooting on plant water status during the growing season of the crop. However, Stone et al. (1976) revealed that the depletion effectiveness (cm^3 of water g^{-1} of root d^{-1}) of roots decreased with time in a given soil layer, and increased with depth in a given time. Not only the distribution of roots, but also its activity plays an important role in water extraction by roots. Even a small portion of the root system can be responsible for a much water uptake.

In general, rooting density is greater in the upper layers than in the lower layers of the rooting zone, and the roots deep within the profile are less effective than those near the soil surface (Klepper et al., 1973). The water content in the lower layers is thus depleted by the two simultaneous processes, viz., uptake by the roots of that layer and the flux divergence, the direction of which would depend upon the directions of the suction gradients. The contribution of lower layers towards the total water uptake increased as the dry period after irrigation advanced (La Rue *et al.*, 1963). The rate of water use increased with the development of crop canopy, but once the maximum leaf area is attained it remained mainly a function of the evaporative demand of the atmosphere (Lal and Sharma, 1976). Nnymah and Black (1977) observed that a good correlation existed between water uptake rate, rooting density and the profile water depletion and results agreed well with the evapotranspiration calculated from the micrometeorological factors.

Gupta and Aggarwal (1977) reported that moisture depletion of 1.50m profile plus water infiltered into the profile during growth period may provide necessary good estimate of seasonal water use by crops. Whereas, Jana *et al.* (1984) reported that moisture extracted from the surface 0-15 cm soil layer was minimum (26.2%) under irrigation at 0.50 atm tension throughout. The moisture extraction pattern from different soil layers decreased successively, with an increase in soil depth in all treatments. Sharma and Ghildyal (1977) reported that the water extraction rate per unit root volume increased significantly with increasing soil water tension. The studies further suggest that root systems that developed under relatively dry soil conditions were capable of extracting greater amount of soil water on a unit root volume basis than those developed under moist conditions.

The rate of water uptake per unit length of root for the whole profile and for individual soil layers generally decreased throughout the period of measurement (Gregory et al., 1978). In all the soil moisture regimes during the initial stage of crop growth upto the crown root initiation stage, the rate of water use was low. Thereafter, the rate of water use increased progressively with the development of crop canopy throughout tillering, booting, flowering and grain filling. Beyond this, in general, there was a fall in the rate of water use due to leaf senesence (Singh and Dastane, 1971; Patil, 1976; Singh and Bhardwaj, 1981).

More than 60 per cent of the total moisture used by wheat was depleted from 0-30 cm layer and thereafter moisture depletion increased with an increase in soil depth (Gupta and Dargan, 1971; Singh et al., 1971; Kumar et al., 1986). Similar observations were also noticed in the irrigated wheat although in unirrigated wheat, moisture depletion was relatively more but absolutely less than the irrigated wheat in deeper layers. This was because the moisture depletion from the upper layers was less in case of unirrigated wheat than the irrigated. This clearly suggested that under restricted moisture, root penetration was better and this extracted more moisture from deeper soil layers (Singh and Bhardwaj, 1981; Kumar et al., 1986). Water uptake was functionally related to rooting density and soil water potential (Ehrler et al., 1980).

Pande _et al_. (1975) reported that the major part, that is to the extent of 85 per cent of the total moisture used by the wheat crop was met from the top 60 cm layer only. In all the soil moisture regimes the maximum depletion was from 0-30 cm soil layer and relatively more moisture was withdrawn from the wet regimes than was the case with the moist and dry regimes. The depletion decreased successively with an increase in depth and time and the lowest depletion occured from the lowest layer. However, moisture depletion from 30-45 cm soil layer was more under low moisture regime than high moisture regime. Similarly, a study by Singh (1978) on consumptive use of water and soil moisture depletion pattern by wheat revealed the greatest soil moisture depletion was from 60 cm soil layer and was 81.2 to 92.3 per cent of the total consumptive use during the two seasons and suggested that the top 60 cm of soil layer should be wetted at each irrigation for efficient utilization of irrigation water.

A study by Prihar _et al_. (1976) showed that water depletion from 1.80m soil profile generally increased with decreasing irrigation water. Maximum profile water depletion occurred when a fixed amount of irrigation was applied. Gogoi (1988) found that out of total moisture depletion, about 85 per cent moisture was depleted from 0-45 cm depth alone and attributed this to (i) the presence of more roots with more activities, and (ii) more evaporation from surface soil. Jaggi _et al_. (1977) reported that deep soil layers (1.00 to 1.50m) contributed about 11 to 13 per cent of seasonal water use by rainfed wheat. Saini and Ghildyal (1978) showed that the contribution of upward flux towards the total water requirement of wheat was 36 to 73 per cent, whereas the soil water depletion accounted for 11 to 19 per cent water.

Van Bavel <u>et al</u>. (1968) reported that the indiscriminate use of soil water depletion rates to represent the evapotranspiration rates without accounting for deep percolation could be highly misleading. Bhagat and Acharya (1988) studied the effect of various soil management practices on soil water dynamics during the growth of rainfed wheat and reported that the soil water flux across root boundary should not be ignored while calculating the crop water requirement from profile water depletion method. Patro and Misra (1985) employed tensiometric techniques to measure the percolation loss below the root zone and showed that it constitutes a considerable fraction of the total consumptive use.

Acharya <u>et al</u>. (1979) reported that in an amended sodic soil root water extraction by raya was mainly confined to a surface (0-15cm) depth. The flux divergence across root boundary was negligible due to poor hydraulic properties of a sodic soil. Kalra <u>et al</u>. (1984) reported that root water extraction rates in wheat were lower in the top soil immediately following irrigation. They observed that this was due to moisture redistribution and presence of younger and active roots which enhanced moisture extraction from the deeper layers.

Singh et al. (1986) studied the effect of water stress at three growth stages of wheat on water use and water use efficiency and noted that water extraction pattern and water use varied markedly with water stress. The maximum water extraction of available soil water was from 0-30 cm soil depth, being highest with no water stress treatment. The per cent extraction of available soil water from this layer decreased with increase in the magnitude of stress particularly during jointing to flowering stage. Most of the available water (39 to 93%) was used from the upper 90 cm soil depth. The water use was higher with no stress treatment and decreased considerably with severe water stress (*15 bar) imposed during jointing to flowering.

2.3 Effect of Nitrogen

Among essential plant nutrients, nitrogen plays an important role in growth and development of plant. It is an important constituent of all proteins that are active component of protoplasm and it is also a constituent of chlorophyll molecule.

2.3.1 Effect of Nitrogen on Root and Plant Growth

The morphology of a plant root system influences the uptake of water and nutrients. Since root morphology of crop plant is altered by routine operation of tillage and nitrogen fertilization (Passioura and Wetselaar, 1972), it is important to understand such alterations and their implications to crop growth. Research has demonstrated that N rates affect three essential components of root morphology (i) length (ii) number of apices, and (iii) frequency of branching. Drew et al. (1973) and Tennant (1976) found that root length increased with N applied to either parts or all of the root system of temperate cereals. Maizlish et al. (1980) studied the root morphology and their early development in maize crop in a pot culture study receiving 0, 21, 42, 145 and 210 ppm of N. Total root length of maize grown at the highest N level increased exponentially from 1.7m at 3 days after emergence to 148m at 17 days after emergence. Root apices increased from 111 to greater than 2900 during the same period. Primary roots (axis) number per plant increased with increasing N, but elongation rate of an individual axis did not respond strongly to increase in N.

Higher levels of N resulted in greater percentage of roots, root diameter (RD), root length density (RLD), root weight density (RWD) and deeper root penetration (Kmoch et al., 1957; Singh and Das, 1986; Orellana et al., 1990). Root weight was significantly higher after the application of 60 kg N ha^{-1}, but with placement at 10-15 cm depth (Rathi and Singh, 1973).

Yield response to N is influenced by level, time and method of its application as well as availability of moisture in the soil (Singh and De Rajat, 1978). Shekhawat et al. (1975) studied response of dwarf wheat to different levels of N (0, 40, 80, 120, 160 and 200 kg N ha^{-1}) and reported that the increasing levels of N (upto 120 kg N ha^{-1}) significantly increased the grain and straw yield of wheat.

A study by Jat et al. (1976a) showed that grain and straw yield of wheat increased with increasing N rates upto 120 kg ha^{-1}. Shrotriya and Misra (1977) reported that leaf area index (LAI) in wheat increased with an increase in N application upto 120 kg ha^{-1} at flowering and grain filling stages. Similarly, the increase in LAI in wheat due to N application has also been reported by Mann (1957) and Srivastava (1968).

Singh and Singh (1979) observed that the application of 120 kg N ha^{-1} increased grain yield of wheat in rice-wheat rotation and the economic N rate for wheat crop was 121.2 kg N ha^{-1}. Chaudhary and Obroi (1984) observed that wheat gave the higher grain yield of 3.84 t ha^{-1} by applying 100 kg N ha^{-1} in three splits under irrigated conditions. In sandy loam soils of Kulu, Tomar et al. (1977) found that wheat yield increased upto 240 kg N ha^{-1}. At Palampur, Sharma et al. (1987) found better growth of wheat crop as a result of improved productivity due to application of N and FYM which resulted in significant improvement in yield attributes and consequently higher yield. Dhiman et al. (1982) found that N application upto 120 kg ha^{-1} increased the grain yield and further increase in N did not show any remarkable yield increase, but at 200 kg N ha^{-1} there was significant decrease in grain yield. In heavy soils of

Patna (Bihar), Chaudhar *et al.* (1987) observed that N had positive effect in increasing the number of grains with increase in N level upto 120 kg N ha^{-1}.

Chandrasekharaiah *et al.* (1985) reported that wheat yields with 50, 100 and 150 kg N ha^{-1} were 2.92, 3.69 and 3.99 t ha^{-1}, respectively. Tiwari (1988) also reported the highest grain yield (40.16 q ha^{-1}) with 120 kg N ha^{-1}. Singh (1990) noted significant increase in grain and straw yield with the application of N upto 120 kg ha^{-1}. The plant height, number of tillers, number of leaves increased significantly only upto 80 kg N ha^{-1}.

2.3.2 Effect of Nitrogen on Water Uptake from Soil Profile

Kmoch *et al.* (1957) found that N fertilization increased root weight of wheat and thereby moisture depletion was evident even upto a depth of 8 feet. Brown (1971) found that daily water use increased as the season progressed and reached maximum value during the heading to flowering stage. He also reported that in unfertilized treatments soil water extraction was largely linked to the upper 91 cm of the soil whereas N fertilized wheat extracted water upto 180 cm depth. Yadav and Agarwal (1981) noted that N application increased the moisture use slightly, but not significantly. Soil moisture extraction pattern did not vary much with N but the contribution of the top 30 cm of profile increased with the number of irrigations.

A study by Reddy and Bhardwaj (1982a) on water use in wheat showed that consumptive use of water increased with 40 to 120 kg N ha^{-1} and 20 to 25 kg P_2O_5 ha^{-1} with marked increase in water use efficiency (WUE), Moisture extraction from the upper soil layers was higher with 1 to 2 irrigations than the adequate irrigations. Chandrasekharaiah et al. (1985) found no effect of N levels (50, 100 and 150 kg N ha^{-1}) on moisture extraction pattern by the wheat crop.

2.4 Interaction Effect of Moisture, Tillage and Nitrogen on Root and Plant Growth and Water Uptake from the Soil

Mathers et al. (1971) worked on the sugarbeet response to deep tillage and N and found that sugarbeet yields were increased by deep tillage and added N, with adequate irrigation but there was no yield increase from applied P. Deep tillage increased yields more when N was applied. Also, the response to N was greater after deep tillage upto 40 cm. A study by Jat et al. (1976a) showed that grain and straw yield of wheat increased with increasing N rates upto 120 kg ha^{-1} and with frequency of irrigations. Singh and De Rajat (1973) studied the effect of different levels of N at varying moisture regimes and found that dry matter accumulation increased with liberal water supply and 100 kg N ha^{-1}.

A study by Singh et al. (1980) on wheat yield under different irrigation regimes and variable fertilization showed that maximum yield (5.09 t ha^{-1}) was with irrigation at 50 per cent available soil water and 120 kg N ha^{-1}. Reddy and

Bhardwaj (1982b) studied the influences of irrigation frequency, levels of N and P on leaf area index (LAI) and leaf area ratio (LAR) in wheat and found that LAI upto 50 days after sowing (DAS) was similar with different irrigation frequencies. At 75 DAS, LAI with the adequate irrigation treatment (irrigation at 0.5 atm tention at 25 cm depth) was higher than with 1 to 2 irrigations and it increased with applied N and P. It was slightly higher with more irrigations than without irrigation. The flag leaf area increased with adequate irrigation and increasing N and P rates.

Moisture extraction from the deeper soil layers was higher with 1 to 2 than the adequate irrigations and with N and P fertilization than without them (Reddy and Bhardwaj, 1982a). Wheat yield responses to increased amounts of residual soil nitrate were much less than to freshly applied N. Yield responses to both sources of N increased with increasing water supply (Prihar et al., 1985). Irrigation and NP application to oat increased the leaf water potential, stomatal conductance and absorption of radiations and all of which increased the fodder yield (Singh et al., 1987). Orellana et al. (1990) obtained significantly higher yields of soya with deep tillage treatments and fertilizer application, but no interaction effect was found. However, deep tillage, unlike fertilizer treatments also resulted in significantly higher plant population compared to conventional tillage owing to improved drainage associated with lower penetrometer resistance, during the exceptionally wet germination emergence period.

A study by Jat et al. (1976b) revealed that higher level of N and moisture resulted in greater percentage of roots in 0-15 cm soil depth as well as within 0-15 cm radius laterally. They also found that decreased N and moisture level led to an increased distribution of roots upto 30 cm depth. Misra et al. (1985) observed the effect of limited input of water on root growth and indicated that whether the soil profile is partially or completely filled with water at sowing, it did not effect the root growth of wheat at 56 days sampling. An irrigation at the nodal root growth initiation stage (30 days after sowing) promoted overall root growth. The root density at 1.20m depth was greater with drilled than with broadcast N. Singh and Das (1986) found that root weight density (RWD), root length density (RLD) and root diameter (RD) increased with N rates. Root length showed a significant positive correlation with soil water depletion and grain yield.

2.5 Water Production Functions (Stress Indices) in Relation to Soil Moisture Regimes and Tillage Depths

The interaction of plant with the environment is complex and leaf water potential is influenced by a number of environmental factors, including the air and soil temperature, absolute humidity, wind velocity and soil water availability (Kaufman and Hall, 1974; Ritchie, 1974). Stegman et al. (1976)

have indicated that relating plant water stress development to variables indicative of prevailing soil and atmospheric environments will enable scheduling irrigation based on plant water stress criteria.

The leaf water status or the level of water stress in plants profoundly influences, virtually all physiological and metabolic functions. In recent years, the measurement of crop water stress has received considerable attention. Todd et al. (1962) emphasized the importance of measuring moisture tension on plant rather than in the soil. Weatherley (1950, 51) proposed the use of disc of leaf tissues which can be floated on water and gave the term relative water content (RWC) and calculated as:

$$\text{RWC} = \frac{\text{Fresh weight - dry weight}}{\text{Full turgid weight - dry weight}} \times 100$$

Water status in plant can also be described by the energy status of plant water or leaf water potential (Hsiao, 1973). Decreased soil moisture leads to decreased leaf water potential and increased stomatal resistance and reduced photosynthesis and thus reduced plant growth (Boyer, 1968; Acevedo et al., 1971). Effects of plant water deficit are specific to plant genotype and need to be evaluated for important species/varieties. Water relations of plant grown in green house have been well studied (Hsiao, 1973) which, however, have limited utility, as marked discrepancies have been reported between water relations of plants grown in controlled environment and in the field (Begg and Turner, 1976).

A study by Rajagopal et al. (1977) on diurnal variation in relative leaf water content (RLWC) of wheat showed that it was lower in stressed plants than in nonstressed ones throughout the 24 h period. Although it was lowest at 12 h, it recovered by 1500 h. Epstein and Grant (1973) found RLWC values of potato leaves for irrigated plants between 80 and 100 per cent against 76 to 87 per cent for unirrigated plants and these values were a function of soil water potential. Tomar and Ghildyal (1973a) noted that wilting phenomenon is not directly related to 15 bar soil water suction and it occurs at a definite value of turgor and is associated with a marked changes in elastic property of leaf. Moorby et al. (1975) studied the diurnal fluctuations of RLWC under irrigated and unirrigated conditions and found that unirrigated plants were not fully turgid at 0530 h and there was little variation in RLWC from 0730 to 1530 h showing dependence on soil water potential. Rajput and Gupta (1978) conducted a study on the effect of soil water potential on leaf water potential of wheat and reported that it decreased linearly with the soil water potential.

Diurnal leaf water potential in sorghum changed rapidly from no plant water stress at dawn to large negative potential in mid afternoon, which suggested that the rate of supply of water was inadequate to meet the demand (Carbon, 1973). Singh et al. (1984) studied the changes in xylem water potential (XWP) of wheat cultivars grown under different soil moisture regimes and reported that XWP decreased at the maximum rate of 0.2 bar per minute for 20 to 30 minutes after sunrise, but within an hour the rate became slow. At sunset the rate of recovery in XWP was more in rainfed than in irrigated wheat.

Fisher (1973) reported that plants exposed to soil drying cycle for a given number of days under carefully controlled conditions may reach different levels of water stress depending on their stage of development. Xylem tension measured on the stem may produce a more useful indication of plant water stress than relative water content of the leaves, especially when effects on the developing ears dominate the overall yield response.

Martin and Dougherty (1975) conducted a study on diurnal variations in the plant water potential of leaves and ears of wheat and indicated that in flag leaves it decreased rapidly in the morning more slowly to a level of about -20 to -22 bars at 1200h and did not recover until evening. The diurnal changes in plant water potential and canopy temperature were documented for wheat by Ehrler et al. (1978b). The diurnal range of plant water potential was considerable from about -10 to -16 bar for well watered plots and -21 to -43 bar for a water deficit plot. The study showed that for canopy temperature measurement, 1400h is the best time of the day to assess water stress. A similar conclusion was also reached by Blad et al. (1981).

Adjel and Kirkham (1980) measured the leaf water potential and stomatal resistance on (a) drought sensitive (b) drought resistant cultivars of wheat and showed that when water was lacking (a) had a lower leaf water potential than did (b). With both daily and weekly watering, stomatal resistance was higher in (b) than in (a) and showed that stomatal resistance was a better index when screening for drought resistance than the determination of leaf water potential. A study was conducted by Katerji _et al_. (1985) on the development of stomatal diffusion resistance and leaf water potential in durum wheat and noted that in a season of frequent rain, the stomatal diffusion resistance of leaves from boot to grain formation growth stage ranged from 1 to 2 scm^{-1} depending on soil water availability. From grain formation to milk ripe, stomatal diffusion resistance values depended principally on plant water status irrespective of soil moisture.

Nagarajarao and Mallick (1980) showed a positive relationship between profile moisture contents and leaf water potential for cowpea, sorghum and maize during the most active physiological stage of growth and beyond this stage, the leaf water potential decreased, inspite of high profile moisture contents. Bharabme _et al_. (1984) noted a linear, positive and highly significant relationship between soil water potential and leaf water potential under different levels of N (0, 40, 80 and 120 kg ha^{-1}). Wallace _et al_. (1983) found that total water potential of wheat leaves decreased in parallel with soil water potential, concurrently leaf osmotic potential also decreased sufficiently to maintain positive leaf turgor potential. Losavio et al. (1984) revealed that during crop development, leaf water potential decreased more rapidly in the rainfed wheat. Stomatal resistance was influenced by soil water content, physiological stage and radiation load, but not by stomatal frequency. The critical leaf water potential for closure of stomata was -20 and -27 bar for irrigated and stressed plants, respectively.

The leaf water potential was lowest in the afternoon and highest at sun-up (0630h) and at this time the plant water status reflects the soil water status (Ritchie, 1974). Nagarajarao (1984) conducted a study on behaviour of leaf water potential of wheat under field conditions. He found that increase of wheat leaf water potential correlated with available soil moisture percentage remaining in the root zone only for reproductive phase of crop growth. For the vegetative phase of growth, no relationship could be established, possibly because of high and non-limiting soil moisture and suggested that for adopting the regressions for irrigation scheduling, important growth phases have to be considered separately. Joubert (1987) made comparison of wheat cultivars with respect to drought resistance and found cultivar differences in dry matter accumulation at the low moisture level suggesting that leaf water potential during the flag leaf stage under moisture stress conditions may be an indicator of difference in tolerance.

Rasico et al. (1987) grew six durum wheat varieties in the field under irrigated or unirrigated conditions. Three indicators of plant water stress, viz., leaf water potential, stomatal diffusion resistance and relative water content were studied. Of the three indicators studied, leaf water potential was the most sensitive and discriminated best among the varieties. Leaf water potential and stomatal diffusion resistance recovered to the level of mild stress, but took considerably longer time following a severe stress. Walker et al. (1987) reported that in wheat leaf water potential recovered in two days following a mild stress, whereas the leaf water potential of the severely stressed treatments never recovered to the control value. The osmotic potential on the other hand remained lower than that of the well watered control for several weeks after stress in wheat crop thus maintaining a higher pressure potential.

Canopy temperature measurement may be better indicator of plant water stress, atleast during the early stages of stress. As the canopy becomes several degrees warmer than air, the temperature difference becomes insensitive to changes in plant water potential (Ehrler et al., 1978a; Blad et al.,1981; Gardner et al., 1981; Heerman and Duke, 1978). Eaten and Belden (1929) measured cotton leaves temperature and found leaf temperature to be 2 to 4°C below that of air, but Curtis (1936) explained their results on the basis that low humidity allowed long wave energy to radiate to the clear cold sky, thus cooling the leaves.

Many scientists have shown that difference between canopy and air temperature (ΔT) is a better criterion of water stress than the plant temperature alone (Palmer, 1967; Carlson, 1972; Ehrler et al., 1978 a,b; Sumayao et al., 1980). Ehrler (1973) reported that saturation vapour pressure deficit of air (SD) influences the sensitivity of T as a reliable indicator of irrigation. He described a procedure for making allowance for variations in SD. Jackson et al. (1977) suggested the use of stress degree days (SDD) computed as the summation of ΔT for determining the timings and amounts of irrigations to crops. Similarly, several research workers (Blad and Rosenberg, 1976; Idso and Ehrler, 1976) have also suggested that the difference between leaf or canopy temperature and air temperature (ΔT) can be used to indicate the plant water stress.

Sandhu and Horton (1978) observed that during hotter part of the day under semi-arid climate, fully exposed leaves of oats subjected to mild to moderate stress were 1 to 4°C warmer than the non-stressed leaves.

Idso et al. (1977) used stress degree days (SDD) to predict final yields in wheat. They plotted cumulative stress degree days (CDSS) from heading to maturity as a function of time for several wheat plots that had received different amount of irrigation water. They showed that CSDD increased steadily with time and a low final grain yield was predicted. The SDD concept was also applied to red kidney beans by Walker and

Hatfield (1979). They found that final yield was inversely related to the SDD and concluded that the SDD is a valid representation of effect of moisture stress on yield.

Nitrogen influences plant water relations (Shimshi, 1970; Radin and Parker, 1979; Radin and Boyer, 1982). Radin and Parker (1979) suggested that N deficiency decreased leaf water potential and suggested that this was caused by increased root resistance to water flow in cotton plants. Radin and Boyer (1982) found that low N strongly decreased the hydraulic conductivity in sunflower plants thereby increasing water deficit in expanding leaf blades.

A study by Mooris and Dayanard (1978) on the influence of soil density on leaf water potential of corn showed that with denser soil, leaf water potential declined more rapidly during dark intervals because of restricted root growth.

2.6 Inter-relationships Between Various Water Production Functions

Kramer (1963) reported that it is not safe to assume that a certain level of water stress is accompanied by equivalent degree of plant water stress. The relative leaf water content is the most suitable approach of measuring leaf water status and has been found to be closely related to the water potential of same tissue. Similar observations have also been made by Gardner and Ehlig (1965) who reported that the relationships between leaf water potential and relative leaf water content were different for different species and age of the plants.

The plant and soil water potentials were same at dawn as the internal gradients disappeared due to little or no evaporative losses. Relative leaf water content was more effected by atmospheric conditions than soil water content (Winker, 1961; Slayter and Gardner, 1965; Faiz and Haysoc, 1978). Tomar and Ghildyal (1973b) studied the relationship between leaf water potential (LWP) and relative leaf water content (RLWC) in rice and investigated the RLWC and LWP at which rice leaves visibly wilted. The LWP decreased sharply as RLWC decreased below 100 per cent, in intermediate RLWC range, the drop in LWP was gradual, but below RLWC of 35 per cent, the drop in LWP was again very sharp.

Ehrler *et al*. (1978a) studied the relationship between wheat canopy temperature and plant water potential and found that the temperature difference between plant canopy and air (ΔT) was related to the plant water potential. Increased drought decreased plant water potential progressively and increased temperature difference accordingly. When plant water potential decreased to -19.0 bar, ΔT was zero. Similarly, when plant water potential was -48 bar, ΔT increased to 4.8^{o}C. Singh and Singh (1984) noted that canopy minus air temperature difference (ΔT) was related to the leaf water potential in field grown wheat under two differential water supplies at

50 and 60 per cent depletion of available soil moisture in the root zone.

Gardner et al. (1981) compared the difference in plant water potential between stressed and non-stressed sorghum and the canopy temperature difference between the two plots. A parabolic relation was found between the difference to a maximum of about 4°C which later decreased. The study further recognized the effect of measurement variability and suggested that stomatal opening and closing may affect relationship between canopy temperature and plant water potential. Katerji (1979) showed a direct relationship between diffusive resistance and leaf water potential in wheat as soil water deficit decreased. Frank et al. (1973) studied the effect of temperature and plant water stress on leaf water potential and leaf diffusion resistance in spring wheat. Measurements were made on the fifth leaf at tillering and the flag leaf at heading, flowering and grain filling growth stages for plants grown at 10, 18 and 27°C. They found that stomatal closure of stressed plant occurred at -13, -13 and -15 bar leaf water potential at tillering, at -18, -17 and -26 bar at heading for 10, 18 and 27°C, respectively. As the flag leaf matured, stomata closed at progressively lower leaf water potential.

The reduction in stomatal aperture increases the resistance to water vapour of the leaves and the transpiration slows down. Several investigators (Van Bavel, 1967; Szeica and Long, 1969; Sandhu and Horton, 1977) have reported that leaf diffusion resistance is closely related to plant water status.

Pal and Varade (1982) noted the influence of soil water potential on transpiration rate, leaf water potential (LWP) and relative water content (RWC) in two aerial environments and found significant and positive correlation between RWC and LWP, RWC and transpiration rate were effected by aerial environments and soil texture. A study by Rasico et al. (1987) on seasonal changes in some indicators of water stress and their variation among wheat genotypes revealed the highest value for leaf water potential and lowest for relative water content. The correlation between leaf water potential and stomatal resistance was significant only in the irrigated treatments.

MATERIALS AND METHODS

MATERIALS AND METHODS

Studies were conducted at the experimental farm of Himachal Pradesh Krishi Vishvavidyalaya, Palampur (Kangra). This place is located between 32°6'N latitude and 73°3'E longitude at an altitude of 1300m above mean sea level. The annual rainfall of the area is around 250 cm. More than 80 per cent of this is received during monsoon. Winter rains are meagre and erratic. The average minimum and maximum temperatures recorded during the first year of crop study ranged from 1.8 to 19.4°C and 10.8 to 30.8°C, respectively. The minimum temperature of 1.8°C on 117 days after sowing (DAS) and maximum of 31.8°C on 172 DAS were recorded during the months of March and April, respectively. In the second year of study the corresponding temperatures ranged from -0.5 to 20.6°C and 6.0 to 30.2°C with minimum of -0.5°C on 56 DAS and maximum of 30.6°C on 183 DAS during the months of December and May, respectively. The rainfall, temperature and open pan evaporation during the wheat growing season are given in Appendix I and II, respectively (for the years 1989-90 and 1990-91).

The soils of the experimental area are classified as Alfisol, Typic Hapludalf. The pH ranges from 5.3 to 5.8. The soils are generally rich in clay content with the accumulation of sesquioxides in the subsurface layers. The organic carbon is around 0.94 per cent.

The present study entitled, "Profile water extraction through water - nitrogen - tillage interaction in wheat" aimed at evaluating the effect of different nitrogen levels, tillage methods and water stocks on water extraction from subsurface depths. The effect of imposed treatments on water stress in wheat, root growth, water extraction pattern, soil - plant - water relations, N content in plant and its uptake, and growth and yield was evaluated.

3.1 Determination of Physical and Physico-chemical Properties of the Study Area

This includes the determination of particle size distribution, aggregate analysis, bulk density, soil physico-chemical properties, soil water retention and transmission characteristics.

3.1.1 Particle Size Distribution

The particle size distribution was done by international pipette method (Piper, 1950). The texture of different profile depths was ascertained by using textural diagram of the International Society of Soil Science.

3.1.2 Aggregate Analysis

The aggregate size distribution analysis was performed with the help of Yoder's apparatus (Yoder, 1936). The apparatus was calibrated to give about 3/4 inch stroke, for 29 strokes per minute. Air dried samples collected from different profiles depths were broken by hand into small crumbs and fractionated by sieving through 8 mm sieve. The material retained in 4 mm sieve was analysed for aggregate size distribution after saturating it over night. The sieve set ('Standard of Geologists Syndicate India Ltd, Calcutta) was immersed in water at about 22±0.5°C. The apparatus was run for 20 minutes. The resulting samples on the respective sieves were oven dried at 105°C and weighed. The different size fractions were calculated. The results were calibrated for the coarse primary particles retained on each sieve to avoid designating them falsely as aggregates. This was done by dispersing the material collected from each sieve using dispersing agent (IN NaOH), stirring it mechanically and finally washing the material back through the same sieve. The weight of sand retained after the second sieving was substracted from the total weight of the dispersed material retained after the first sieving and percentage of stable aggregates (SA) was calculated using the relation (Kemper, 1965) as follows:

$$\% \text{ SA} = \frac{\text{Weight retained - weight of sand}}{\text{Weight of total sample - weight of sand}} \times 100 \quad ..(1)$$

The mean weight diameter (MWD) was computed with the help of procedure as outlined by Van Bavel (1949)

$$\text{MWD} = \frac{\sum_{i=1}^{n} \text{di Wi}}{\sum_{i=1}^{n} \text{Wi}} \quad ..(2)$$

where di is the mean diameter of each size fraction(mm) and Wi the weight of that fraction in the sample (g).

3.1.3 Bulk Density

The bulk density was determined by core method (Singh, 1980) using a metallic core (11.5 cm height and 8 cm internal diameter). The core has a sharp edge at the bottom to facilitate easy penetration into the soil and 1.0 cm thick open circular cap fitting on the edge of the core at the top. A profile at the experimental site was excavated upto 90 cm depth. The core was driven into the soil by hammering with a centre weight concentrated hammer. Three cores for each depth were removed at an increment of 15 cm upto 90 cm depth. The soil was freshly weighed and moisture content determined by gravimetric method. The dry bulk density was calculated using mass volume relationship.

3.1.4 Soil Physico-chemical Properties

Soil pH was determined in 1:2.5 soil water suspension and the organic carbon was estimated by wet digestion method (Walkley and Black, 1934). Available N was determined by alkaline permanganate method (Subbiah and Asija, 1956), available P by Olsen's method (Olsen et al., 1954) and available K by neutral normal ammonium acetate method (Morwin and Peach, 1951). The cation exchange capacity was determined by neutral normal ammonium acetate method as described by Black (1965).

3.2 Soil Water Retention and Transmission Characteristics

3.2.1 Laboratory Determinations

3.2.1.1 Retention Characteristics: Undisturbed soil core samples, drawn in metal rings (3 cm long and 5 cm diameter), were collected in triplicate, from a profile exposed in the study area, from the different depths upto 90 cm with the help of a core sampler (Cat. No. 200A, manufactured by Soil Moisture Equipment Corp, Santa Barbara, California, USA). The samples were wrapped in polyethylene bags and stored in the refrigerator for further use.

Moisture content (θ) at different matric suctions (Ψ) ranging from 0 to 15000 m bar was determined with the help of pressure plate apparatus. Soil samples were saturated for 24 hours and then equilibrated against applied pressure. The water content was determined gravimetrically and converted into volumetric water content by multiplying with bulk density of the corresponding depth. Soil moisture characteristic curves were drawn for different depths by plotting suction (Ψ) Vs water content (θ) on a simple scale. The retention data were fitted to the equation of the type (Gardner, 1970)

$$\Psi = a\theta^{b} \qquad .. \ (3)$$

where Ψ is the soil water suction (mbar), θ is the soil water content on volume basis ($cm^{3}cm^{-3}$) and a and b are the constants.

3.2.1.2 Saturated Hydraulic Conductivity: The undisturbed soil cores having soil column thickness of 3 cm and diameter of 8 cm were collected in triplicate from each 15 cm depth increment upto 90 cm depth. The cores were wrapped in polyetheylene envelopes, properly packed and transported to the laboratory.

Saturated hydraulic conductivity (K_s) was determined by constant head method. K_s was calculated by Darcy's equation (Richard, 1954) as:

$$K_s = \frac{Q}{At} \cdot \frac{\partial H}{\partial Z} \qquad \ldots\ldots \qquad (4)$$

where, K_s = Saturated hydraulic conductivity (cm d^{-1})

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

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

t = Time (d)

H = Hydraulic head (cm)

Z = Depth of soil in the column (cm)

$\frac{\partial H}{\partial Z}$ = Hydraulic gradient (cm cm^{-1})

3.2.2 Field Determinations

3.2.2.1 Drainage Characteristics: Changes in soil water content 'W' with time 't' at different depths for the internally draining profile were fitted to the relation of the type (Richards *et al.*, 1956):

$$W = at^{n} \qquad \ldots\ldots \qquad (5)$$

The data were plotted on a log-log scale and the constants a and n evaluated for different depths.

3.2.2.2 Hydraulic Conductivity: The hydraulic conductivity of different depths of the soil profile of the experimental site was determined by the method as described by Hillel et al. (1972). The data of the internal drainage of profile was analysed as under:

The general equation describing flow of water in a vertical soil profile is

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial Z} \left(K (\theta) \frac{\partial H}{\partial Z} \right) \quad .... \quad (6)$$

where, θ is the volumetric wetness, t the time, Z the vertical depth taken positive downward, K is the hydraulic conductivity which is a function of soil wetness and H is hydraulic head.

Integrating eq. (6), we get

$$\int_0^Z \frac{\partial \theta}{\partial t} \, dZ = K \left(\frac{\partial H}{\partial Z} \right)_z \quad .... \quad (7)$$

$$\frac{\partial \theta}{\partial t} Z = K \left(\frac{\partial H}{\partial Z} \right)_z \quad .... \quad (8)$$

where Z is the soil depth to which the measurements are applied. If the soil surface is covered to prevent evaporation and only internal drainage is allowed, the total water content change per unit time is given by

$$\left(\frac{dW}{dt}\right)_z = K\left(\frac{dH}{dZ}\right)_z = q \quad \ldots. \quad (9)$$

where, W is the total water content of the profile upto depth Z i.e.

$$W = \int_0^Z \theta \, dZ \quad \ldots. \quad (10)$$

Finally, eq. (9) gives

$$K = q/dH/dZ \quad \ldots. \quad (11)$$

The data obtained for hydraulic conductivity (K) Vs moisture content (θ) were fitted to the equation of the type

$$K = ae^{b\theta} \quad \ldots. \quad (12)$$

where a and b are the empirical constants.

3.3 Treatment Details

The experiments were conducted for two years during *rabi* 1939-90 and 1990-91 with wheat (*Triticum aestivum* Linn. emend. Fiori and Paol.) as a test crop. Wheat (VL 421) was seeded on 6th November during both the years of study. One presown irrigation during both the years was given before field preparation. The sowing was done in rows 20 cm apart in 5 x 2m plots. The details of the treatments are as follows:

3.3.1 Nitrogen

Three levels of N, viz., 40, 30 and 120 kg ha^{-1} designated as N_{40}, N_{30} and N_{120}, respectively were applied through urea (46% N). Fifty per cent of N was applied at sowing and the rest in two equal splits, at maximum tillering and flowering stages. Phosphorus and potash were applied as basal doses with 60 kg ha^{-1} of P as single superphosphate and 30 kg ha^{-1} K as muriate of potash, respectively.

3.3.2 Tillage

Two tillage methods, viz., conventional tillage (T_1) upto 15 cm depth and deep ploughing (T_2) upto 30 cm depth with turning of soil were followed.

3.3.3 Water Stocks

Three variable water stocks (W_1, W_2 and W_3) around maximum tillering stage of wheat crop, depending upon the initial water content were imposed. This was accomplished by applying different depths of water at this stage depending upon the antecedent water stocks in 0 to 90 cm profile depth. Before and after this stage, the crop was grown under rainfed conditions.

The treatments were imposed in Split Plot Design having combinations of nitrogen levels and tillage methods in main plots and three variable water stocks in sub plots. The treatments were replicated three times in 10 m^2 plots making a total of 54 plots (2x3x3x3). The scheme of treatments is summarised in Table 1.

Table 1: Scheme of treatments

Main Plot: Combinations of three levels of nitrogen (N) and two tillage (T) methods

Nitrogen (N) levels

N_{40}	40 kg N ha^{-1}
N_{80}	80 kg N ha^{-1}
N_{120}	120 kg N ha^{-1}

Tillage (T) methods

T_1	Conventional tillage (manual digging with spade upto 15 cm depth)
T_2	Deep ploughing (manual digging with spade upto 30 cm depth and turning of soil)

Sub Plot: Three variable water (W) stocks viz., W_1, W_2 and W_3 through application of variable amounts of water depending upon the initial water stocks in 0 to 90 cm profile at maximum tillering.

Replications	3
Plot size	5 x 2 m
Total number of plots	54

Water stocks were made variable 75 DAS during both the years of study and various plant-water stress indices were evaluated during crown root initiation (35 DAS), maximum tillering (77 DAS), and flowering (150 DAS) stages.

3.4 Soil Studies During the Crop Growth

3.4.1 Soil Water Content

The changes in soil water content during crop growth at increments of 15 cm upto 90 cm depth were monitored with the help of Neutron moisture meter at weekly intervals and on the day followed by rain during the whole crop growth period. Al- access tubes were installed only in one of the replications. The water content for 0-15 cm and 15-30 cm depths were determined gravimetrically.

3.4.2 Soil Water Potential

Mercury manometer tensiometers at different depths (15, 30, 45, 60, 75 and 90 cm) were installed in one of the replications (having Al- access tubes) to monitor the changes in hydraulic gradients at different depths and time during the crop growth.

3.5 Evaluation of Crop Water Stress

The different parameters of water stress viz., relative leaf water content (RLWC), xylem water potential (XWP), leaf diffusion resistance (LDR) and stress degree days (SDD) were evaluated at important growth stages, i.e. crown root initiation, maximum tillering and flowering, as follows:

3.5.1 Relative Leaf Water Content

Relative leaf water content (RLWC) of fully exposed leaf (second from the top) of mother shoot was computed from the fresh weight, turgid weight and oven dry weight, at maximum tillering the flowering stages according to the method given by Weatherley (1950):

$$\text{RLWC} = \frac{\text{Fresh weight} - \text{Oven dry weight}}{\text{Fully turgid weight} - \text{Oven dry weight}} \times 100 \quad \ldots (13)$$

3.5.2 Xylem Water Potential

Xylem water potential (XWP) was recorded using a portable pressure chamber apparatus (Waring and Cleary, 1967). Observations were taken during mid-day (1200-1400 h) under full sunlight and diurnal changes were recorded from 0800 to 1700 h. At crown root initiation whole plant was taken for measurement after cutting from the ground level. At other growth stages fully exposed leaf, second from the top, was selected. Three leaves per treatment were sampled at each time of the day.

3.5.3 Leaf Diffusion Resistance

An automatic porometer MK-3 (Delta-T Devices Ltd., Burwell, Cambridge, England) was used on the intact leaves to measure the leaf diffusion resistance (LDR). The porometer was calibrated for different temperatures and relative humidity ranges. Observations were taken at maximum tillering and flowering stages of wheat growth during mid-day (1200 to 1400 h) under full sunlight on the fully exposed second leaf from the top of the mother shoot.

3.5.4 Stress Degree Days

Stress degree days (SDD) were recorded from maximum tillering to dough stage of wheat growth with the help of Telatemp Infra-Red-Thermometer (IR Thermometer). The measurements were made during mid-day (1200 to 1400 h). The IR thermometer was directed over the crop canopy at 30° angle and six observations were taken in each treatment. Stress degree days were calculated as described by Jackson *et al.* (1977)

$$SDD = T_c - T_a \qquad \ldots. \qquad (14)$$

where, SDD = Stress degree days (°C)

T_c = Crop canopy temperature (°C)

T_a = Air temperature (°C)

$$CSDD = \sum_{i=1}^{n} SDD \qquad \ldots. \qquad (15)$$

where, CSDD = Cumulative stress degree days (°C)

n = Number of observations

3.6 Root Studies

Root growth parameters, viz., root mass density (RMD), root volume and root length density (RLD) were determined at important growth stages, i.e. crown root initiation, maximum tillering, flowering and at harvest of wheat crop during the years 1989-90 and 1990-91. Metallic cores (10.3 cm internal diameter and 13.4 cm height) were excavated from previously randomly selected rows, selected for biomass production. The cores were kept in water, overnight, and then roots were made free from soil by washing with fine jet of water. The roots were collected on fine sieves for final washing with a microjet tap.

Root length was measured in a glass bottomed shallow dish of 40 x 20 cm dimensions. Graph paper ruled in mm was placed below the dish. The wet roots were cut from the root shoot joint and spread randomly into the dish containing some water with the help of forceps and needle so that they did not overlap. The long branched roots were cut into smaller pieces. The counts for intersections of roots (N) with vertical and horizontal lines of 1 cm grid from the graph paper were recorded. Care was taken to avoid more than 400 counts at one instance (Kopke, 1979). Root length was computed using the modified version of Newman (1966) formula as proposed by Marsh (1971) and Tennant (1975) as:

$$\text{Root length (R)} = \frac{11}{14} \text{ X number of intersections (N) X grid unit} \quad \ldots \quad (16)$$

Total root length was divided by the volume of the core to compute root length density.

The volume of roots was determined by displacement method and divided by the volume of the core to compute the roo volume per unit volume of soil. Roots were then transferred to filter paper and pressed gently in its folds to remove imbibed water. The roots were then dried in an oven at 60°C to a consta weight and finally the dried weight was taken. The dry weight was divided with the volume of the core to compute the root weight density.

3.7 Root Water Uptake

Data on soil water content and potential were first analysed to estimate soil water flux (V_z, cm d^{-1}) using Darcy's law, as:

$$V_z = -K_z \left(\frac{\partial H}{\partial Z}\right)_z \quad \ldots\ldots \quad (17)$$

where, K is the hydraulic conductivity (cm d^{-1}) and H is the hydraulic head, being the sum of suction head (h) and the gravitational head (Z), Z being the depth to which the measurements apply.

The rate and pattern of water uptake by roots at a given depth were obtained from the rate of change of soil water content ($\frac{d\theta}{dt}$) and flux divergence ($\frac{dV_z}{dZ}$) at the depth (Ogata et al., 1960) as under:

$$-\frac{d\theta}{dt} = \frac{dV_z}{dZ} + r_z \quad \ldots\ldots \quad (18)$$

or

$$-\ r_z = \frac{d\theta}{dt} + \frac{dV_z}{dZ} \quad \ldots\ldots \quad (19)$$

where, V_z is positive downward and r_z (cm^3 of water cm^{-3} of soil d^{-1} or d^{-1}) is the water uptake by roots at depth Z. Since r_z is the sink term, hence a negative quantity. To obtain R_z (cm d^{-1}), which is the sum total of water extraction by roots and evaporation, r_z is integrated over a given depth interval in the root zone, i.e.

$$R_z = \int_0^Z r_z dZ \quad \ldots. \quad (20)$$

To apply eqs. (19) and (20), selected time interval representing active growth period of crop was choosen. Changes in water content $(\frac{d\theta}{dt})$ for selected time interval were determined. Then using K Vs θ relations established <u>in situ</u>, values of K were found out for each value of θ. Using eq. (17) the flux V_z was calculated and then values from successive profiles were averaged to obtain V_z values. These were then differentiated with respect to depth to obtain flux divergence $(\frac{dV_z}{dZ})$. Values of r_z were then calculated using eq (19). R_z, which is the sum of water extraction by roots and evaporation, was obtained by numerically integrating 'r_z' values over the root zone.

3.8 Profile Water Depletion

The profile water depletion (ΔS_z) was calculated by taking the difference of water stocks during two time intervals (t_1=140 day, t_2=170 day) and was calculated with the help of equation given below:

$$\Delta S_z = \int_0^Z \int_{t_1}^{t_2} \frac{d\theta}{dt} dZdt \quad \ldots. \quad (21)$$

where, ΔS_z, profile water depletion (cm) for 0 to 90 cm depth; t, time (d); Z, depth (cm) and θ, volumetric wetness ($cm^3 cm^{-3}$).

3.9 Leaf Area Index

Number of tillers in one metre row length of randomly selected rows were counted. The leaf area of leaves of five tillers was recorded on Area Measurement System MK-2 (Delta - T Devices Ltd. Burwell, Cambridge, England). This value when multiplied by the number of tillers in one metre row length gave the leaf area per metre row length. For convenience of presentation and interpretation, these values were then converted to total leaf area per plot (sq. metre). Leaf area index (LAI) was calculated by the formula given by Redford (1967) as follows:

$$\text{LAI} = \frac{\text{Leaf area}}{\text{Ground Area}} \quad \ldots. \quad (22)$$

3.10 Dry Matter Accumulation

The dry matter accumulation was recorded at three important growth stages, viz., crown root initiation, maximum tillering and flowering. The plants were clipped, closest possible to ground level, in 50 cm row length from randomly selected rows. The plant samples were then oven dried at 60°C to a constant weight. The values obtained were converted into dry weight and expressed as g m^{-2}.

3.11 Crop Yield

The wheat crop was harvested at maturity on May 14 and 8 in the years 1990 and 1991, respectively. The grain and straw yields were recorded and expressed on per hectare basis.

3.12 Nitrogen Content and Uptake

Nitrogen concentration was determined at crown root initiation, maximum tillering, flowering and at harvest by the method outlined by Jackson (1973). Nitrogen uptake was calculated by multiplying the N content with dry matter yield.

3.13 Meteorological Parameters

The data for rainfall, temperature and open pan evaporation were procured from the observatory of the Department of Agronomy, HPKV, Palampur, located at about 200 m from the experimental site.

3.14 Statistical Analysis

The data were analysed using standard statistical techniques described by Cochran and Cox (1963).

EXPERIMENTAL RESULTS

EXPERIMENTAL RESULTS

The experimental results are presented under the following broad headings:

4.1 Soil physical and physico-chemical properties

4.2 Soil studies during crop growth

These include changes in soil water content, hydraulic gradients and hydraulic flux (at 32.5 cm) during a typical drying period under different treatments.

4.3 Water withdrawal pattern

This includes the water uptake by the roots, total water extraction rate and per cent contribution of water by different profile depths.

4.4 Comparison of profile water depletion and total root water uptake

4.5 Root studies

These include the root mass density, root volume and root length density at different growth stages and at harvest.

4.6 Evaluation of crop water stress

This includes the determination of relative leaf water content, xylem water potential, leaf diffusion resistance and stress degree days.

4.7 Soil-plant-water relations

These include the relationships between different water production functions such as relative leaf water content, xylem water potential and leaf diffusion resistance with soil moisture storage, soil water potential.

4.8 Plant growth studies

These include the leaf area index, dry matter production, grain and straw yield, nitrogen content in plant and its uptake at different growth stages and at crop harvest in grain and straw.

4.1 Soil Physical and Physico-Chemical Properties

4.1.1 Particle Size Distribution, Aggregate Analysis and Bulk Density

The particle size distribution, textural class, bulk density, mean weight diameter (MWD) of aggregates, and water retention at 100, 330 and 15000 mbar are given in Table 2. The data reveal that the clay content is maximum (32.9%) in 30-45 cm and minimum (28.8%) in 60-75 cm layer. The clay content in the surface (0-15 cm) layer is less than the other profile layers. Also the surface layer (0-15 cm) showed the maximum percentage of silt (49.6%) which gradually decreased with depth upto 90 cm. The total amount of sand (coarse plus fine) is minimum (20.6%) in 0-15 cm depth, which increased with depth and became maximum (37.3%) in 75-90 cm depth. The textural class of the different profile layers is silty clay loam.

The mean weight diameter (MWD) of aggregates (Table 2) did not show any consistent trend with depth and its values for different profile depth increments of 0-15, 15-30, 30-45, 45-60, 60-75 and 75-90 cm were 2.43, 1.82, 2.46,

Table 2: Some basic soil properties of the experimental site

Depth (cm)	Mechanical separates (%) Clay	Silt	Sand	Textural class	Bulk density (Mg m^{-3})	MWD (mm)	Moisture content (% by volume) Suction (m bar) 100	330	15000
0 - 15	29.4	49.6	20.6	Silty clay loam	1.10±0.02	2.43±0.05	33.0	27.0	17.0
15 - 30	32.2	41.8	25.3	Silty clay loam	1.17±0.01	1.82±0.09	34.5	29.5	19.5
30 - 45	32.9	40.2	25.4	Silty clay loam	1.24±0.03	2.46±0.07	37.5	34.5	20.8
45 - 60	29.5	38.5	31.5	Silty clay loam	1.26±0.02	2.01±0.13	39.0	36.0	26.0
60 - 75	28.8	37.2	33.6	Silty clay loam	1.33±0.01	2.19±0.13	43.5	38.5	27.5
75 - 90	31.5	30.8	37.3	Silty clay loam	1.36±0.02	2.31±0.12	45.0	39.5	28.7

Bulk density (Mg m^{-3})		1989-90	1990-91
(i) Conventional tillage (T_1)			
	0-15 cm	1.10±0.02	1.05±0.03
	15-30 cm	1.25±0.02	1.22±0.02
(ii) Deep ploughing (T_2)			
	0-15 cm	1.04±0.03	0.99±0.05
	15-30 cm	1.14±0.02	1.09±0.02

2.01, 2.19 and 2.31 mm, respectively. Maximum value of 2.46 mm was obtained for 30-45 cm and minimum of 1.82 mm for 15-30 cm soil layer.

The bulk density value of different profile depths showed an increasing trend with the depth (Table 2). Maximum bulk density value of 1.36 Mg m^{-3} was obtained for 75-90 cm profile layer and minimum of 1.10 Mg m^{-3} for surface layer of 0-15 cm.

After the imposition of tillage treatments, the bulk density under deep ploughing and turning of soil lowered down both in surface (0-15 cm) and subsurface (15-30 cm) depths compared to the treatment of conventional tillage (Table 2).

Soil moisture characteristic curves for undisturbed soil samples are depicted in Fig.1 whereas the water retention at some selected suction values are given in Table 2. The volumetric water content (θ) at all depths decreased with increase in suction(Ψ). The values of 'θ' at 100, 330 and 15000 mbar for 0-15 cm depth are 33.0, 27.0 and 17.0 per cent, respectively, whereas, the respective values for 75-90 cm depth at these suctions were 45.0, 39.5 and 28.7 per cent. The water retention increased with depth at all suction values (Fig.1). There was an abrupt decrease in water content with an increase in 'Ψ' upto a value of 100 mbar and beyond this value the decrease in water content with increase in 'Ψ' became gradual. The resulting empirical relationships from the data

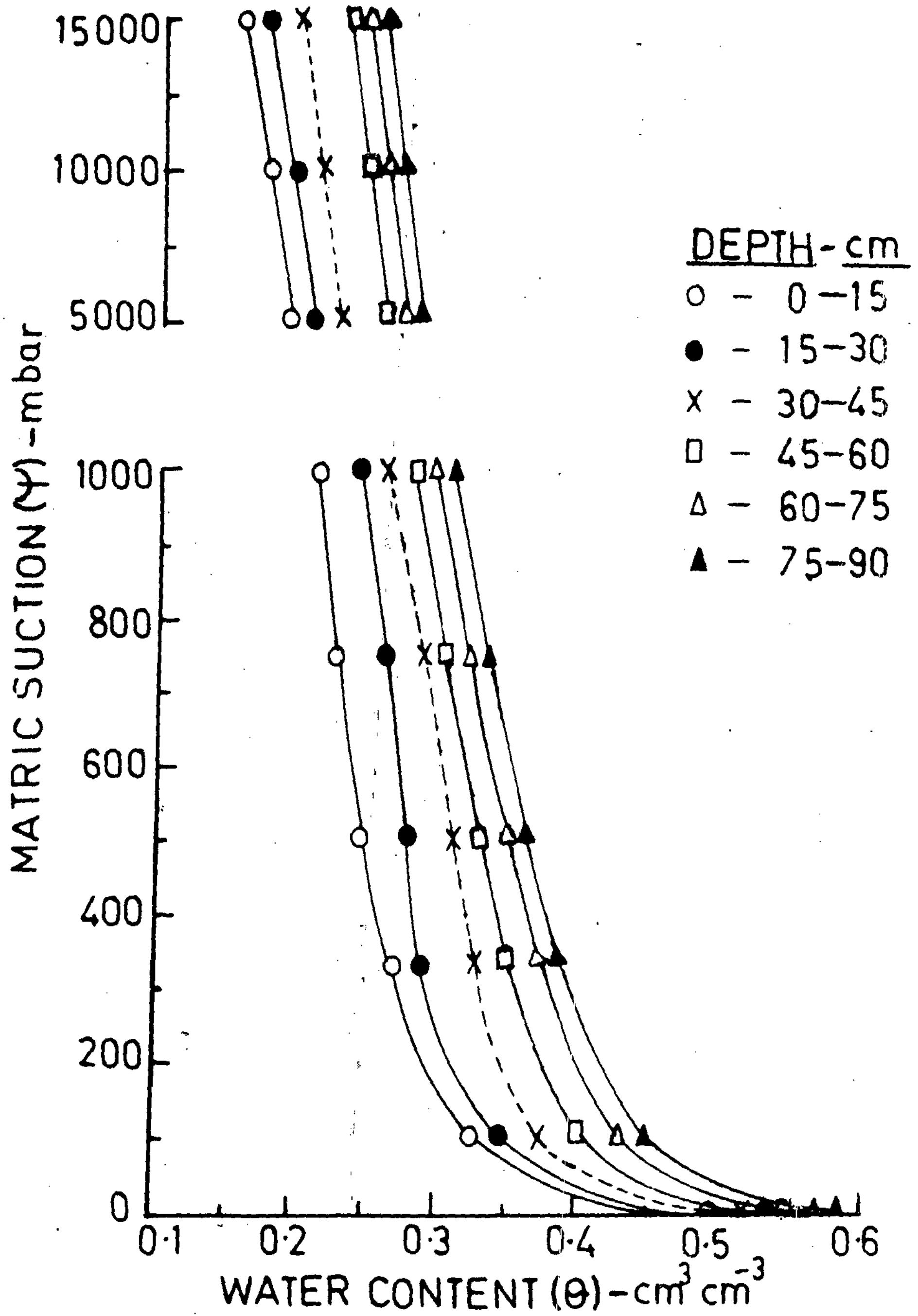


Fig.1 Soil moisture characteristics of the experimental site

are shown in Table 3. The constant 'b' which is indicative of change of suction with water content showed an increasing trend with depth upto 75 cm, beyond which its value decreased.

4.1.2 Drainage Characteristics

The drainage characteristics of the study area are presented in Fig.2. The data showed that amount of water drained down the profile increased with depth and the rate of drainage decreased with depth. The resulting empirical relationships from the data are shown in Table 3. The constant 'n' which is indicative of the average rate of decrease of water content with time was the lowest for 0-90 cm profile layer (0.03) and maximum for 0-15 cm layer (0.09).

4.1.3 Hydraulic Conductivity

4.1.3.1 Saturated Hydraulic Conductivity: The saturated hydraulic conductivity (K_s) values determined in the laboratory for different profile depths at 15 cm depth interval upto 90 cm depth are presented in Table 3. The depthwise distribution of 'K_s' showed a decreasing trend. Upto 45 cm depth there was an abrupt decrease and below this the decrease is gradual.

4.1.3.2 Unsaturated Hydraulic Conductivity: The unsaturated hydraulic conductivity '$K(\theta)$' values obtained *in situ* for different layers are presented in Fig.3. The '$K(\theta)$' values for 0-15, 15-30 and 30-45 cm depths were comparable and are grouped in one empirical relationship (Table 3). Similarly, the values

Table 3: Some important soil water functional relationships

Depth (cm)	$\psi = a\ \theta^{b}$	$W = at^{n}$	K_s	$K = ae^{b\theta}$	
0 - 15	$4\times10^{-2}\ \theta^{-7.11}$	$7.24\ t^{-0.09}$ (0-15 cm)	26.22	$0.0015e^{10.63\theta}$	0-45 cm
15 - 30	$3\times10^{-2}\ \theta^{-7.88}$	$14.13\ t^{-0.06}$ (0-30 cm)	23.07	$0.0015e^{10.63\theta}$	
30 - 45	$4\times10^{-2}\ \theta^{-8.24}$	$21.88\ t^{-0.05}$ (0-45 cm)	17.41	$0.0015e^{10.63\theta}$	
45 - 60	$6.9\times10^{-3}\ \theta^{-10.75}$	$28.84\ t^{-0.05}$ (0-60 cm)	13.82	$0.0003e^{14.89\theta}$	45-90 cm
60 - 75	$9.6\times10^{-3}\ \theta^{-11.33}$	$36.31\ t^{-0.04}$ (0-75 cm)	12.10	$0.0003e^{14.89\theta}$	
75 - 90	$2\times10^{-2}\ \theta^{-10.85}$	$43.65\ t^{-0.03}$ (0-90 cm)	10.37	$0.0003e^{14.89\theta}$	

where ψ, Metric suction (mbar); θ, Volumetric water content ($cm^3 cm^{-3}$); W, Soil water storage (cm); K, Unsaturated hydraulic conductivity ($cm\ d^{-1}$); t, time (d); a and n, constants; K_s, saturated hydraulic conductivity ($cm\ d^{-1}$)

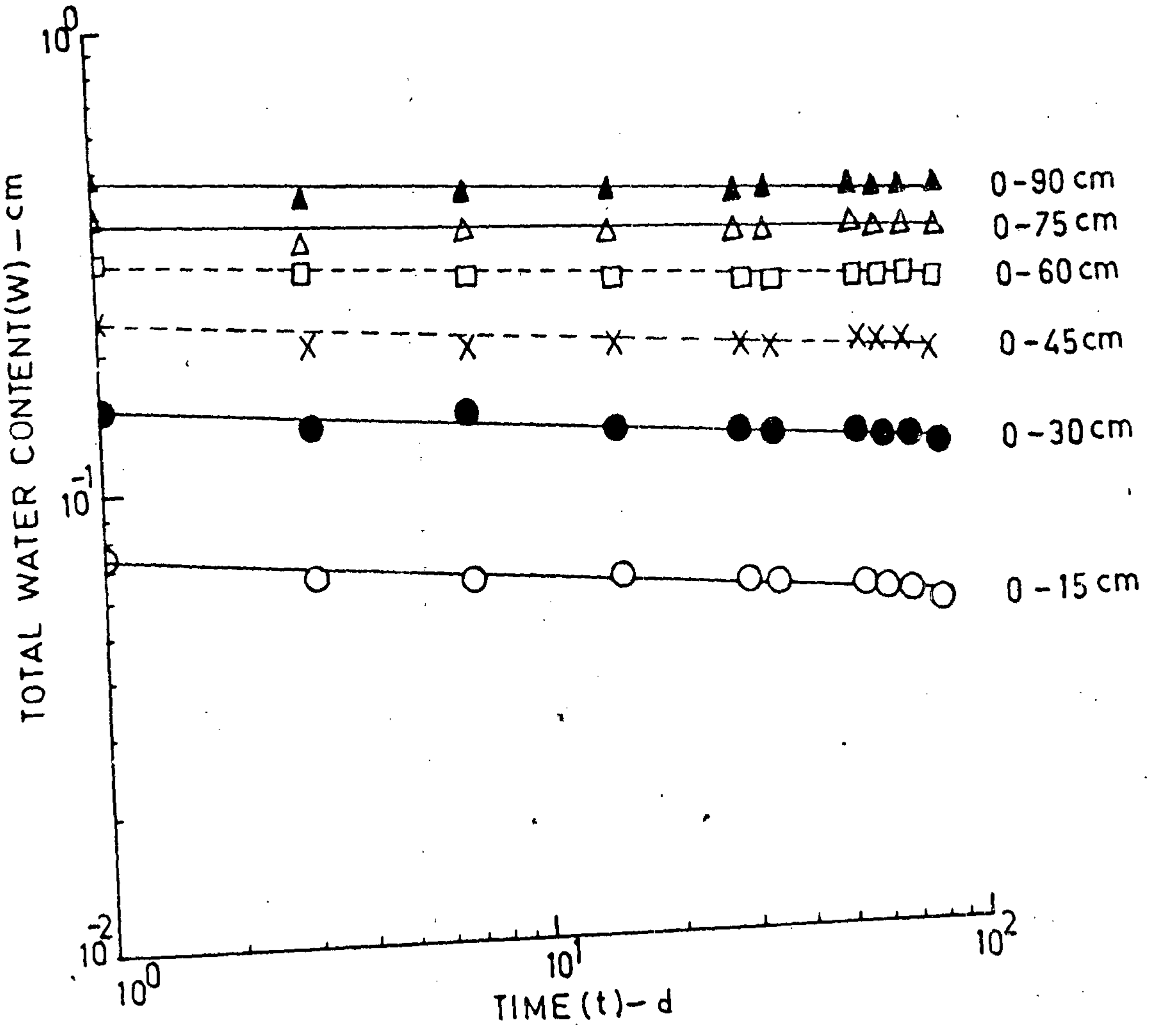


Fig.2 Drainage characteristics of the experimental site

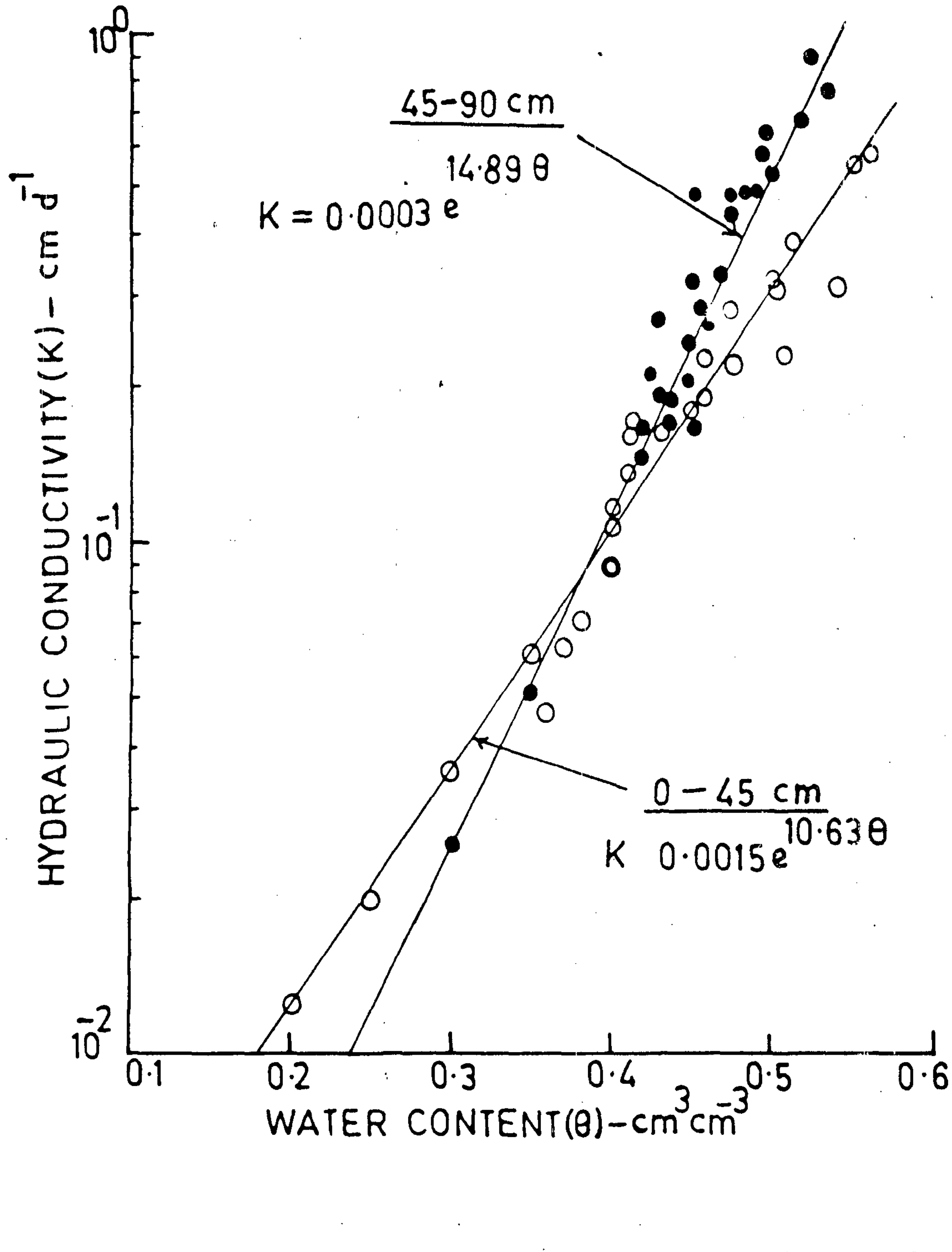


Fig.3 Field determined hydraulic conductivity values of the experimental site

for 45-60, 60-75 and 75-90 cm depths were also comparable and grouped in one empirical relationship. The magnitude of difference between the two layers, i.e. 0-45 cm and 45-90 cm was increasing with an increase in water content. At 39 per cent volumetric wetness the values of '$K(\theta)$' were equal for the two layers and above this wetness, the values of '$K(\theta)$' were more for 45-90 cm as compared to 0-45 cm depth.

The functional dependence of 'K' upon 'θ' was worked out for the entire water content range for all depths and resulting empirical relationships are depicted in Table 3. The slope 'b' of the equation is an indicative of the change of hydraulic conductivity 'K' with water content 'θ'. The values of constant showed an increasing trend with depth and its values for 0-45 and 45-90 cm depths were 10.63 and 14.89, respectively.

4.1.4 Soil Physico-chemical Properties

Soil chemical and physico-chemical properties of the study area for 0-15 cm depth are shown in Table 4. The soil of the experimental site is acidic in reaction, medium in per cent organic carbon, available, N, P and K.

Table 4: Some chemical and physico-chemical properties of the study area (0-15 cm depth)

pH	5.5
O.C.	0.94%
CEC	14.0 Cmol (p+) kg^{-1}
Available N	252 kg ha^{-1}
Available P	17 kg ha^{-1}
Available K	216 kg ha^{-1}

4.2 Soil Studies During Crop Growth

4.2.1 Changes in Soil Water Content

The changes in soil water content on some selected days during a typical drying period (March 25 to April 24) from 140 to 170 days after sowing (DAS) in the first year of the study under different main plot treatment combinations are depicted in Fig.4 (a, b, c, d, e, f). This dry period corresponds with flowering and dough growth stages of wheat for which various stress indices and water uptake are also calculated. The figures show that the water content in the surface 0-15 cm layer under all the treatments was less than the water content in the lower layers. As the dry period advanced, surface (0-15 cm) layer lost water rapidly to the atmosphere in comparison to the subsurface layers. The decrease in water content from 0-15 cm layer was maximum (30.5 to 13.0%) under the treatment combination of $N_{120}T_2$ and was equal to the decrease under $N_{120}T_1$ (37.5 to 20.0%). The decrease in water content from this layer in the treatments of $N_{40}T_1$, $N_{80}T_1$, $N_{40}T_2$ and $N_{80}T_2$ was 30.3 to 17.3, 35.3 to 18.8, 34.0 to 23.3 and 33.5 to 16.3 per cent, respectively, which turned out to be 1.95, 2.48, 1.61 and 2.53 cm, respectively, as compared to 2.63 cm under both the treatments of $N_{120}T_1$ and $N_{120}T_2$.

In 15-30 cm layer the water content under all the treatments decreased as the dry period progressed, but the maximum decrease from 38.5 to 25.3 per cent (1.98 cm) was

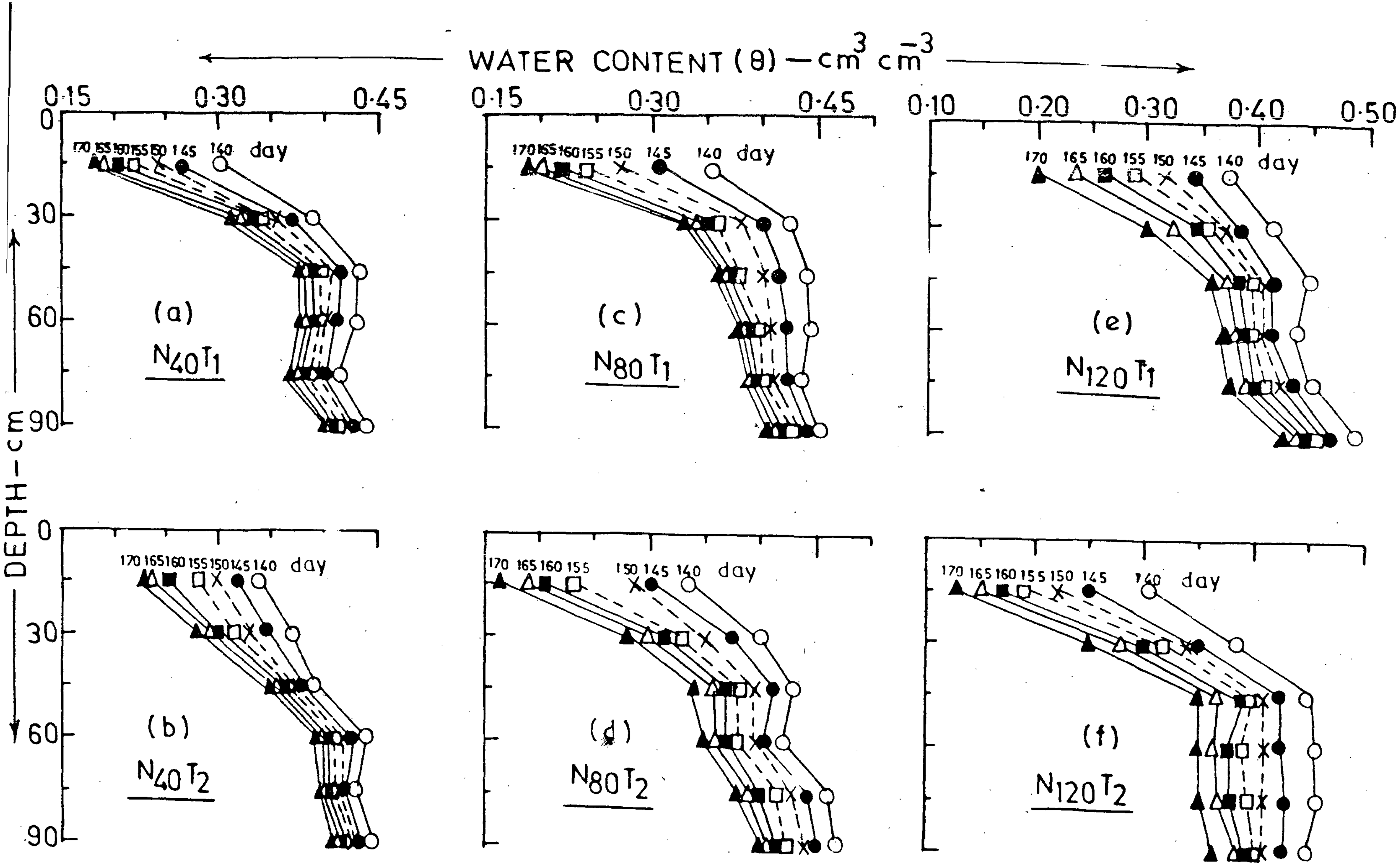


Fig.4 Changes in soil water content under various treatments during a typical drying period from 140 to 170 days after sowing

observed in the treatment of $N_{120}T_2$, followed by the treatment of $N_{80}T_2$, being 40.0 to 28.3 per cent (1.76 cm). Corresponding changes in this layer (15-30 cm) under the treatments of $N_{40}T_1$, $N_{80}T_1$, $N_{120}T_1$ and $N_{40}T_2$ were 39.0 to 32.5, 42.5 to 33.8, 41.3 to 30.0 and 36.8 to 28.3 per cent which are equal to 0.98, 1.31, 1.79 and 1.28 cm, respectively.

Soil water content in 30-45 cm layer decreased under all the treatments as the dry period progressed. Maximum decrease (45.0 to 35.8%) from this layer occurred in the treatment of $N_{120}T_1$ which was equal to the change under $N_{120}T_2$ (45.0 to 35.8%). The corresponding decreases for this layer under the treatments of $N_{40}T_1$, $N_{80}T_1$, $N_{40}T_2$ and $N_{80}T_2$ were 43.5 to 38.3, 43.8 to 35.8, 39.0 to 36.0 and 43.0 to 34.3 per cent, which are equal to 0.78, 1.20, 0.45 and 1.31 cm, respectively, as compared to 1.38 cm under the treatments of $N_{120}T_1$ and $N_{120}T_2$.

For 45-60 cm layer the maximum decrease in water content was in $N_{120}T_2$ (from 45.8 to 34.8 per cent) followed by the treatments of $N_{80}T_2$ (42.8 to 35.0%), $N_{120}T_1$ (43.5 to 37.0%), $N_{80}T_1$ (44.3 to 38.0%), $N_{40}T_2$ (44.3 to 39.3%) and $N_{40}T_1$ (43 to 38.3%) which are equal to 1.65, 1.17, 0.98, 0.95, 0.75 and 0.71 cm, respectively. There were slight changes in water content for 60-75 and 75-90 cm, depths under different treatments.

Comparison of changes in water content for different treatments under different depths revealed that the maximum decrease under $N_{40}T_1$, $N_{80}T_1$, $N_{40}T_2$ and $N_{80}T_2$ occurred in 0-15 cm and 15-30 cm depths, however, in case of $N_{120}T_1$ and $N_{120}T_2$ the maximum decrease was upto 30-45 cm depth. Total soil water content in the profile upto 90 cm depth on the first day (140 DAS) of the drying period was highest in $N_{120}T_1$ (43.6%) followed by $N_{80}T_1$ (42.5%) and the lowest in $N_{40}T_1$ (40.2%) and on the last day (170 DAS) of drying period the highest water content was in $N_{40}T_2$ (40.3%) followed by the treatment of $N_{120}T_1$ (33.8%) and the lowest in $N_{120}T_2$ (30.0%).

4.2.2 Changes in Hydraulic Gradients

The changes in hydraulic gradients with time during a typical drying period from 140 to 170 DAS during the first year of study under different main plot treatment combinations are shown in Fig.5 (a, b, c, d, e, f). The figures show that in general, the hydraulic gradients for 15-30 cm depth remained upward for most of the time under $N_{80}T_1$, $N_{120}T_1$, $N_{80}T_2$ and $N_{120}T_2$ whereas in case of $N_{40}T_1$, and $N_{40}T_2$ these were downward or near the zero line of gradients upto day 150 and thereafter became upward as the dry period advanced. The upward increase in hydraulic gradients for 15-30 cm depth was more in $N_{120}T_2$ (-14cm cm^{-1}) followed by $N_{120}T_1$ (-12 cm cm^{-1}) whereas for other treatments these were comparable.

For 30-45 cm depth, the value of hydraulic gradients changed from 0.0, +0.6, -1.3, +0.4, -1.8 and -0.4 cm cm^{-1} (on day 140) to -4.0, -4.8, -4.0, -7.4, -7.0 and -4.0 cm cm^{-1}

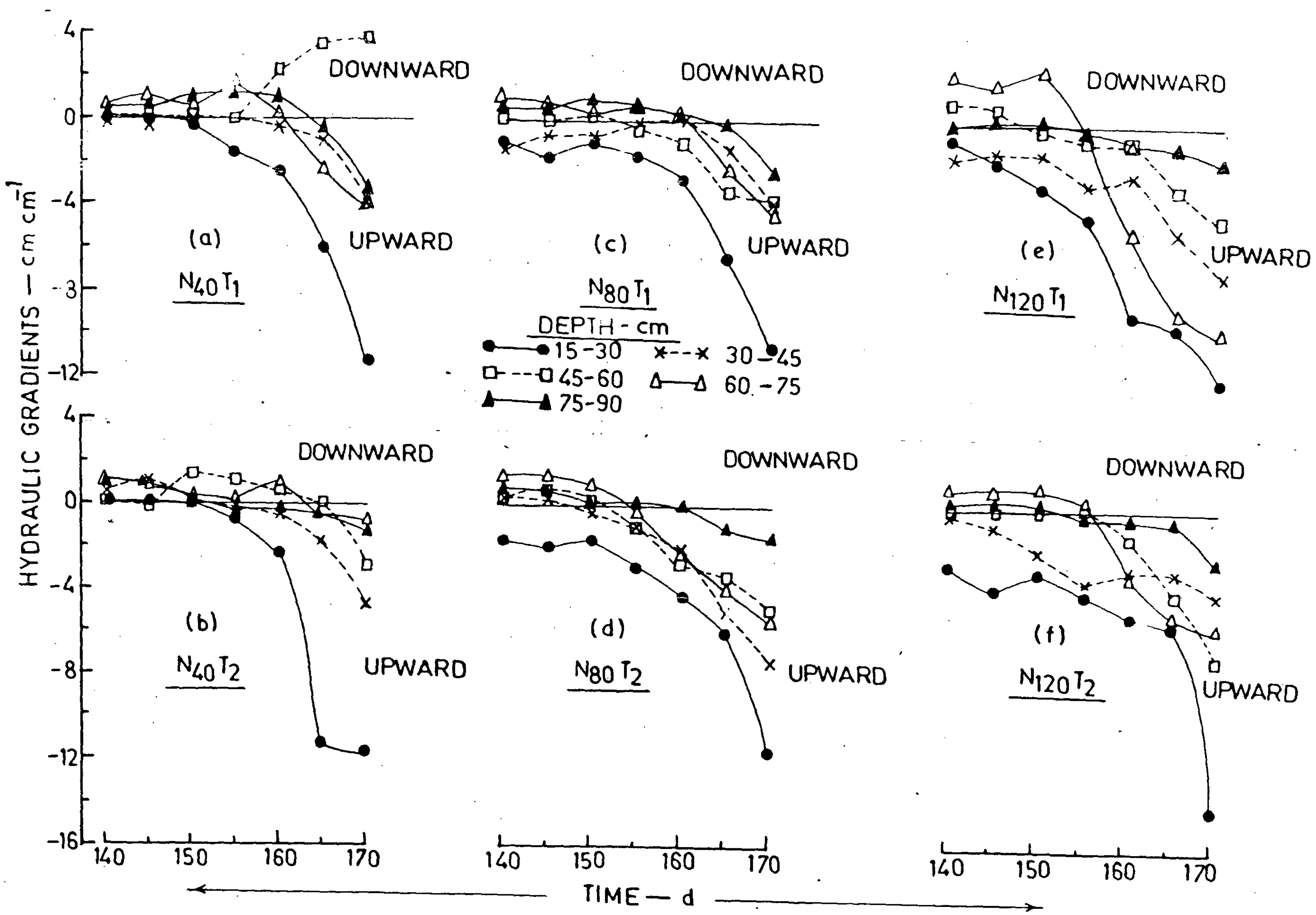


Fig. 5 Changes in hydraulic gradients under various treatments during a typical drying period from 140 to 170 days after sowing

(on day 170) under the treatments of $N_{40}T_1$, $N_{40}T_2$, $N_{80}T_1$, $N_{80}T_2$, $N_{120}T_1$ and $N_{120}T_2$, respectively.

For 45-60 cm depth the maximum change in hydraulic gradients was under $N_{120}T_2$ (0 to -7.0 cm cm^{-1}) followed by $N_{80}T_2$ (0.2 to -4.8 cm cm^{-1}) and $N_{40}T_2$ (0 to -3.0 cm cm^{-1}). Under $N_{40}T_1$ the gradients remained downward (0 to +3.6 cm cm^{-1}), whereas, in other treatments the gradients varied from 1.0 to -4.4 cm cm^{-1}. Similarly, for 60-75 cm depth the maximum increase was under $N_{120}T_1$ (2.0 to -9.6 cm cm^{-1}) and minimum in $N_{40}T_2$ (1.0 to -0.8 cm cm^{-1}) and under other treatments the gradients changed between 1.4 and -5.6 cm cm^{-1}.

The changes in hydraulic gradients for 75-90 cm depth were almost negligible under all the treatments.

A critical analysis of Fig. 5 (a, b, c, d, e, f) shows that changes in hydraulic gradients were more in surface (15-30 cm) layer under all the treatments in comparison to subsurface layers. The hydraulic gradients remained upward for most of the time under various treatments in surface depths. The changes in other depths were more under the treatments of $N_{80}T_2$, $N_{120}T_1$ and $N_{120}T_2$.

4.2.3 Changes in Hydraulic Flux

The changes in hydraulic flux at 82.5 cm depth under different main plot treatment combinations for a drying period from 140 to 170 DAS are depicted in Fig.6. The flux on day 140 under different treatments was downward, being maximum under $N_{40}T_2$ (0.80 cm d^{-1}) and minimum under $N_{120}T_1$ (0.1 cm d^{-1}).

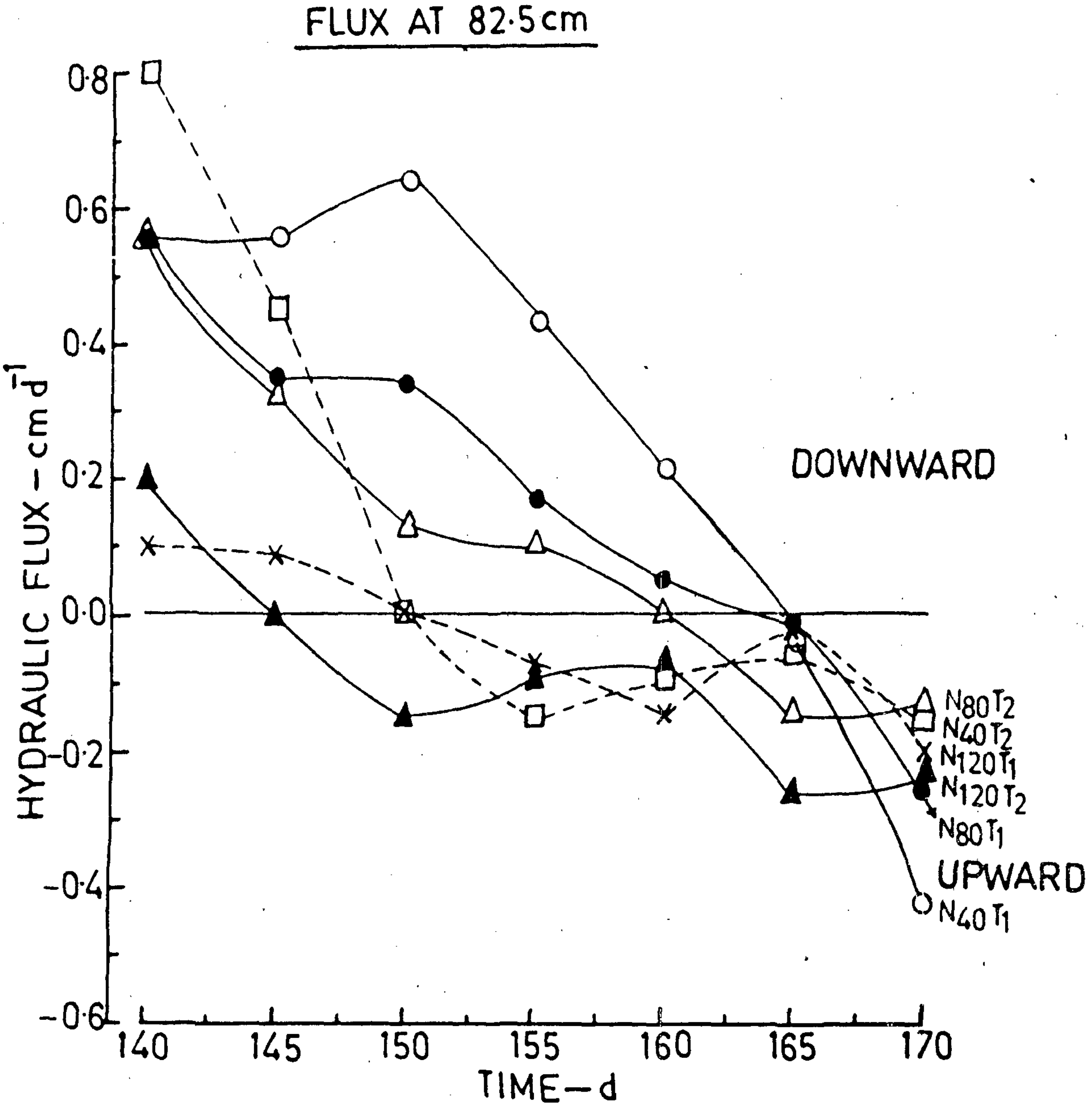


Fig.6 Changes in hydraulic flux across 82.5 cm depth under various treatments during a typical drying period from 140 to 170 days after sowing

There were no differences in the value of flux under the treatments of $N_{40}T_1$, $N_{80}T_1$ and $N_{80}T_2$ on 140th day and it remained around 0.56 cm d^{-1}. The flux remained downward upto 160, 164 and 165 days under $N_{80}T_2$, $N_{80}T_1$ and $N_{40}T_1$, respectively, upto 150 days under $N_{120}T_1$ and $N_{40}T_2$, for a very small period under $N_{120}T_2$. The flux under $N_{40}T_1$, $N_{80}T_1$ and $N_{80}T_2$ treatments decreased slowly with time and became upward after 165, 164 and 160 days, respectively, whereas under $N_{120}T_1$, $N_{40}T_2$ and $N_{120}T_2$ on days 150, 150 and 145, respectively. At the end of drying period, i.e. on day 170, the flux became upward under all the treatments and the maximum value was observed under $N_{40}T_1$ (0.42 cm d^{-1}) whereas under other treatments its value changed between 0.13 to 0.26 cm d^{-1}.

4.3 Water Withdrawal Pattern

4.3.1 Water Uptake by Roots

The water uptake by wheat roots under different main plot treatment combinations for a typical drying period, i.e. from 140 to 170 DAS for the first year of study is shown in Fig.7 (a, b, c, d, e, f). The water uptake 'r_z' (including evaporation) from 0-15 cm layer was maximum under $N_{120}T_2$, being 0.0062 d^{-1} followed by $N_{80}T_2$ (r_z=0.0058 d^{-1}) and minimum under $N_{40}T_1$ (r_z=0.0040 d^{-1}). Whereas, for 15-30 cm layer the maximum and minimum values of 'r_z' were observed under $N_{80}T_2$ and $N_{40}T_1$, being 0.0087 and 0.0038 d^{-1}, respectively. The respective values for 30-45 cm layer were noted under $N_{120}T_1$

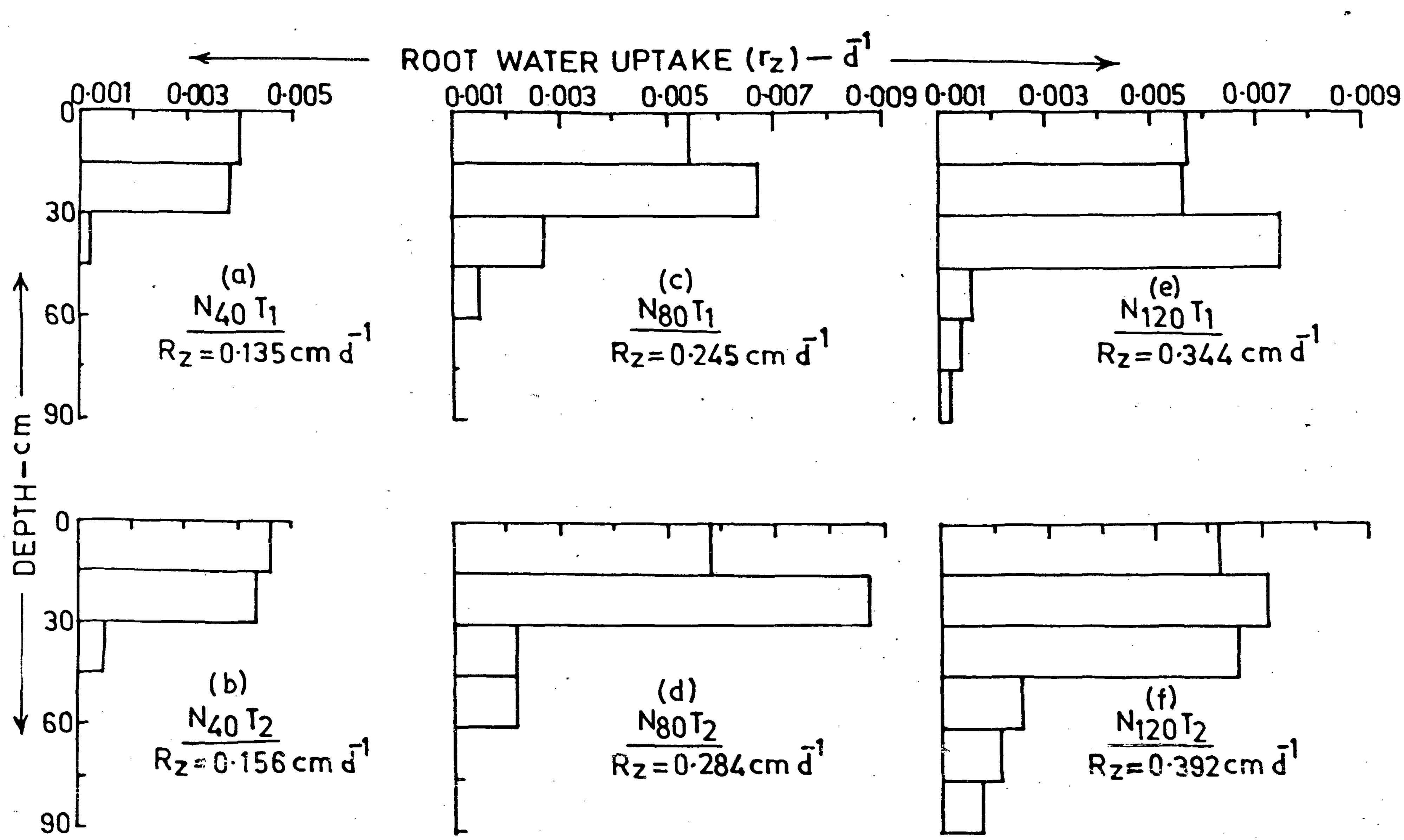


Fig.7 Water uptake by crop roots under various treatments during a typical drying period from 140 to 170 days after sowing

(r_z=0.0074 d^{-1}) and $N_{40}T_1$ (r_z=0.0012 d^{-1}). The treatments of $N_{40}T_1$ and $N_{40}T_2$ did not show any root water uptake below 45 cm depth whereas under $N_{80}T_1$ (r_z=0.0015 d^{-1}) and $N_{80}T_2$ (r_z=0.0022 d^{-1}) it was observed upto 60 cm depth. Likewise, the treatments of $N_{120}T_1$ and $N_{120}T_2$ extracted water from lower layer of 75-90 cm as well, the values being 0.0012 and 0.0017 d^{-1}, respectively.

4.3.2 Total Water Extraction Rate

The 'R_z' which includes the total water uptake plus surface evaporation (Fig.7 a, b, c, d, e, f) was maximum under the treatment of $N_{120}T_2$ (0.392 cm d^{-1}) followed by the treatmentssof $N_{120}T_1$ (0.344 cm d^{-1}), $N_{80}T_2$ (0.234 cm d^{-1}), $N_{80}T_1$ (0.245 cm d^{-1}), $N_{40}T_2$ (0.156 cm d^{-1}) and minimum under the treatment of $N_{40}T_1$ (0.135 cm d^{-1}).

4.3.3 Per cent Contribution of Water by Different Profile Depths

The per cent contribution to the total water uptake of water by different profile depths under different main plot treatment combinations, N levels and tillage methods is shown in Table 5. An examination of the data revealed that the treatments of $N_{40}T_1$ and $N_{40}T_2$ extracted maximum (44.4 and 44.2%) and equal percentage of water from 0-15 cm depth. The treatments of $N_{80}T_1$, $N_{80}T_2$, $N_{120}T_1$ and $N_{120}T_2$ extracted 33.1, 30.6, 24.9 and 23.7 per cent water, respectively. From 15-30 cm depth, the treatment of $N_{80}T_2$ extracted the highest percentage (46.0%) of water and the treatment $N_{120}T_1$ the lowest (24.4%). From 30-45 cm

Table 5: The per cent of the total water depletion from different profile depths under various treatments, nitrogen levels and tillage methods

Treatments	Depths (cm)					
	15	30	45	60	75	90
$N_{40}T_1$	44.4	42.2	13.1	-	-	-
$N_{80}T_1$	33.1	41.0	16.5	9.2	-	-
$N_{120}T_1$	24.9	24.4	32.3	7.0	6.1	5.2
$N_{40}T_2$	44.2	41.3	14.4	-	-	-
$N_{80}T_2$	30.6	46.0	11.6	11.6	-	-
$N_{120}T_2$	23.7	27.1	24.9	9.6	8.0	6.5
Nitrogen levels (N)						
N_{40}	43.3	41.8	13.8	-	-	-
N_{80}	31.9	43.5	14.1	10.4	-	-
N_{120}	24.3	25.8	28.7	8.3	7.1	5.9
Tillage methods (T)						
T_1	34.1	35.9	20.6	5.4	2.0	1.7
T_2	32.8	38.1	17.0	7.1	2.7	2.2

depth the treatments of $N_{40}T_1$ (13.1%) and $N_{40}T_2$ (14.4%) extracted very less percentage of water compared to $N_{120}T_1$ (32.3%) and $N_{120}T_2$ (24.9%) treatments. There was no water extraction below 45 cm depth under the treatments of $N_{40}T_1$ and $N_{40}T_2$. However, the treatments of $N_{80}T_1$ and $N_{80}T_2$, $N_{120}T_1$ and $N_{120}T_2$ extracted 9.2, 11.6, 7.0 and 9.6 per cent of water, respectively from 45-60 cm depth. Like $N_{40}T_1$ and $N_{40}T_2$, there was no water extraction below 60 cm depth under the treatments of $N_{80}T_1$ and $N_{80}T_2$. The treatments of $N_{120}T_1$ and $N_{120}T_2$ extracted water upto 90 cm depth, the percentage being 6.1 and 8.0 for 60-75 cm layer and 5.2 and 6.5 for 75-90 cm layer, respectively.

The maximum extraction of water (50 to 85%) occurred from 0-30 cm depth under different treatments, N levels and tillage methods (Table 5). The per cent contribution of water by different profile depths to total water uptake followed no consistent trend upto 30 cm layer both under N levels and tillage methods. But beyond this layer, the trend was decreasing under N_{80}, the per cent water extractions were 14.1 and 10.4 from 30-45 and 45-60 cm depths, respectively. Similarly, at N_{120}, it was 28.7, 8.3, 7.1 and 5.9 per cent from 30-45, 45-60, 60-75 and 75-90 cm depths, respectively. Conventional tillage (T_1) extracted 20.6, 5.4, 2.0 and 1.7 per cent water from 30-45, 45-60, 60-75 and 75-90 cm, depths, respectively. The corresponding per cent extrations under T_2 were 17.0, 7.1, 2.7 and 2.2.

4.4 Comparison of Profile Water Depletion (ΔS_z) and Total Root Water Uptake (R_z x 30 days)

The per day profile water withdrawal and total water uptake during a typical drying period from 140 to 170 DAS calculated by the method of Ogata et al. (1960) and with the help of eq. (21) is presented in Tables 6a and 6b. The profile water depletion (ΔS_z) was calculated by taking the difference in profile water stocks from 0 to 90 cm depth during two time intervals (t_1=140 day, t_2=170 day). The ds/dt calculated for 0 to 90 cm depth obtained from eq. (21) did not correspond with the R_z (Table 6a), calculated by the method of Ogata et al. (1960). In ds/dt the flux (V_z), for each treatment was not adjusted. When this was done, the values became quite close to R_z.

The total water use under various treatments (Table 6b) during the drying period obtained from eq. (21), i.e. ΔS_z and calculated by the method of Ogata et al. (1960), i.e. R_z x 30 days also did not match. When the fluxes were adjusted in ΔS_z (profile water depletion) then $\Delta S_z \pm$ cumulative flux at 82.5 cm depth (during 140 to 170 DAS) and the total root water uptake (R_z x 30 days) became close to each other.

The total water use (calculated from R_z x 30 days) was the highest under the treatment $N_{120}T_2$, being 11.76 cm and the lowest in $N_{40}T_1$, being 4.05 cm (Table 6b). It increased from 4.37 cm to 11.04 cm with increase in N level from 40 to 120 kg ha^{-1}.

Table 6a: Comparison of profile water depletion (ΔS_z) and total root water uptake (R_zx30 days)

Treatments	R_z (cm d^{-1})	Profile water depletion (ΔS_z) (cm)	$\frac{ds}{dt}$ (cm d^{-1})	Cumulative flux at 82.5cm depth during 140 to 170 DAS (cm)	Flux (V_z) (cm d^{-1})	Profile water withdrawal rate after adjusting fluxes ($\frac{ds}{dt} \pm V_z$) (cm d^{-1})
$N_{40}T_1$	0.135	5.55	0.19	+1.89	+0.06	0.13
$N_{80}T_1$	0.245	7.28	0.24	+1.20	+0.04	0.20
$N_{120}T_1$	0.344	8.89	0.30	-0.65	-0.02	0.32
$N_{40}T_2$	0.156	4.83	0.16	+0.81	+0.03	0.13
$N_{80}T_2$	0.284	9.00	0.30	+0.86	+0.03	0.27
$N_{120}T_2$	0.392	10.54	0.35	-0.59	-0.02	0.37

$$\Delta S_z = \int_0^Z \int_{t_1}^{t_2} \frac{d\theta}{dt}\, dz\, dt \qquad \ldots\ldots \qquad (21)$$

where ΔS_z, Profile water depletion for 0 to 90 cm depth; t, time (t_1 = 140 day, t_2 = 170 day); Z, depth (cm); R_z, water uptake (cm d^{-1}); V_z, flux (cm d^{-1})

Table 6b: Total water use under various treatments during a typical drying period from 140 to 170 days after sowing

Treatments	Water uptake during the period from 140 to 170 DAS (R_zx30) (cm)	Profile water depletion from 0 to 90 cm depth (ΔS_z) (cm)	Cumulative flux at 82.5cm depth during 140 to 170 DAS (cm)	Total water use after adjusting the fluxes (cm) during the drying period(140 to 170 DAS) (cm)
$N_{40}T_1$	4.05	5.55	+1.89	3.66
$N_{80}T_1$	7.35	7.28	+1.20	6.26
$N_{120}T_1$	10.32	8.89	-0.65	9.53
$N_{40}T_2$	4.68	4.83	+0.81	3.87
$N_{80}T_2$	8.52	9.00	+0.86	8.14
$N_{120}T_2$	11.76	10.54	-0.59	11.13

	R_zx30 day	From profile depletion method
N_{40}	4.37	3.77
N_{80}	7.94	7.20
N_{120}	11.04	10.33
T_1	7.24	6.48
T_2	8.32	7.71

Similarly, under tillage methods the total water use was higher under T_2 (8.32 cm) in comparison to T_1 (7.24 cm).

4.5 Root Studies

The root growth parameters (0-30 cm depth) viz., root mass density (RMD), root volume and root length density (RLD) studied at important growth stages and at harvest of wheat crop during the years 1989-90 and 1990-91 are presented in Tables 7, 8 and 9.

4.5.1 Root Mass Density

The data depicting the influence of different N levels, tillage methods and water stocks on RMD in 0-30 cm depth at different growth stages, viz., crown root initiation, maximum tillering, flowering and at crop harvest are presented in Table 7. The root mass density at different depths and growth stages are given in Appendix IV for the years 1989-90 and 1990-91. An examination of the data (Table 7) reveals that at crown root initiation there was no effect of N levels on RMD during both the years of study. Nitrogen had significant influence on RMD at maximum tillering, flowering and at crop harvest stages during both the years of study. At maximum tillering stage, RMD significantly increased from 0.10×10^6 to 0.15×10^6 mg m^{-3} with an increase in N level from 40 to 120 kg ha^{-1} during the year 1989-90. During the year 1990-91, the increase with N level was not significant, but 120 kg N ha^{-1} gave significantly higher (0.17×10^6 mg m^{-3}) RMD over 40 kg

Table 7: Effect of nitrogen levels, tillage methods and water stocks on root mass density (mg m^{-3} x 10^6) at different stages and harvest of wheat crop

Treatments	1989-90				1990-91			
	Stages of wheat growth							
	CRI	MT	FS	AH	CRI	MT	FS	AH
Nitrogen levels (N)								
N_{40}	0.05	0.10	0.15	0.18	0.05	0.13	0.17	0.17
N_{80}	0.06	0.12	0.20	0.25	0.06	0.15	0.21	0.26
N_{120}	0.07	0.15	0.24	0.29	0.07	0.17	0.32	0.30
CD 0.05	NS	0.01	0.04	0.03	NS	0.03	0.08	0.04
Tillage methods (T)								
T_1	0.06	0.12	0.19	0.22	0.05	0.14	0.20	0.23
T_2	0.06	0.14	0.20	0.25	0.06	0.16	0.26	0.26
CD 0.05	NS	0.01	NS	0.02	NS	NS	NS	NS
Water stocks (W)								
W_1		0.13 (35.0)	0.18 (31.2)	0.23 (30.7)				
W_2		0.13 (36.4)	0.20 (30.8)	0.23 (30.1)				
W_3		0.12 (37.3)	0.20 (31.1)	0.26 (31.0)				
CD 0.05		NS	NS	NS				

CRI=Crown root initiation, MT=maximum tillering, FS=Flowering stage, AH=At harvest

Figures in parentheses are water stocks (cm)

N ha^{-1} (0.13×10^6 mg m^{-3}). At flowering stage RMD increased significantly from 0.15×10^6 mg m^{-3} (N_{40}) to 0.20×10^6 mg m^{-3} (N_{80}), but N_{80} and N_{120} were at par with each other. During the second year RMD increased significantly from 0.17×10^6 mg m^{-3} at N_{40} to 0.32×10^6 mg m^{-3} at N_{120}. The significant increase with N level was from 80 kg N ha^{-1} (0.21×10^6 mg m^{-3}) to N_{120} (0.32×10^6 mg m^{-3}). At crop harvest RMD increased significantly from 0.18×10^6 mg m^{-3} at N_{40} to 0.29×10^6 mg m^{-3} at N_{120} during 1989-90 and 0.17×10^6 mg m^{-3} at N_{40} to 0.26×10^6 mg m^{-3} at N_{80} during the second year, but N_{80} (0.26×10^6 mg m^{-3}) and N_{120} (0.30×10^6 mg m^{-3}) were at par with each other.

The effect of tillage methods on RMD (Table 7) was not significant at crown root initiation and flowering stages during the year 1989-90 and at all the growth stages during the second year of study, but numerically T_2 always produced higher RMD than T_1 treatment at all the growth stages. The RMD under tillage methods significantly increased from 0.12×10^6 (T_1) to 0.14×10^6 mg m^{-3} (T_2) and 0.22×10^6 (T_1) to 0.25×10^6 mg m^{-3} (T_2) at maximum tillering and at crop harvest, respectively during the year 1989-90.

There was no significant effect of water stocks on RMD (Table 7) at any of the growth stages during the year 1989-90. During the second year of study, these observations were not recorded.

In general, it was observed that there was appreciable effect of N levels on RMD than the tillage methods during both the years of study. The increase in RMD with time from crown root initiation to maximum tillering was more than two times and to flowering stage it was three times of the value at crown root initiation both under N levels and tillage methods. The increase under N levels from crown root initiation to maximum tillering during the year 1989-90, being 0.05×10^6, 0.06×10^6 and 0.08×10^6 mg m^{-3} and from maximum tillering to flowering being 0.03×10^6, 0.05×10^6 and 0.05×10^6 mg m^{-3} at N_{40}, N_{80} and N_{120}, respectively. The corresponding increases during these stages for the second year were 0.08×10^6, 0.09×10^6 and 0.10×10^6 mg m^{-3}; 0.04×10^6, 0.06×10^6 and 0.15×10^6 mg m^{-3}. Under tillage methods, T_1 and T_2, during the year 1989-90, the increases were 0.06×10^6 and 0.08×10^6 mg m^{-3} from crown root initiation to maximum tillering and 0.07×10^6 and 0.06×10^6mg m^{-3} from maximum tillering to flowering, respectively. The respective increases for the year 1990-91 were 0.09×10^6 and 0.10×10^6mg m^{-3}; 0.06×10^6 and 0.10×10^6mg m^{-3}. Similarly, the increases in RMD under water stocks were 0.05×10^6, 0.07×10^6 and 0.08×10^6mg m^{-3} from maximum tillering to flowering at W_1, W_2 and W_3, respectively.

4.5.2 Root Volume

The effects of various levels of N, tillage methods and water stocks on root volume recorded at different growth stages, viz., crown root initiation, maximum tillering, flowering and at harvest during the years 1989-90 and 1990-91 are given in Table 8. A perusal of the data reveals that there was significant

Table 8: Effect of nitrogen levels, tillage methods and water stocks on root volume ($m^3m^{-3}x\ 10^{-3}$) at different stages and harvest of wheat crop

Treatments	1989-90				1990-91			
	Stages of wheat growth							
	CRI	MT	FS	AH	CRI	MT	FS	AH
Nitrogen levels (N)								
N_{40}	0.48	0.99	1.25	1.40	0.51	0.72	0.95	0.98
N_{80}	0.51	1.12	1.41	1.62	0.52	0.94	1.18	1.44
N_{120}	0.65	1.26	1.82	2.09	0.72	1.08	1.66	1.70
T CD 0.05	0.04	0.16	0.18	0.22	0.05	0.18	0.50	0.38
Tillage methods (T)								
T_1	0.52	1.07	1.39	1.61	0.55	0.89	1.22	1.26
T_2	0.56	1.18	1.60	1.80	0.62	0.94	1.40	1.48
CD 0.05	NS	NS	0.08	0.08	NS	NS	NS	NS
Water stocks (W)								
W_1		1.08 (35.0)	1.46 (31.2)	1.67 (30.7)				
W_2		1.11 (36.4)	1.52 (30.8)	1.70 (30.1)				
W_3		1.18 (37.3)	1.51 (31.1)	1.74 (31.0)				
CD 0.05		NS	NS	NS				

CRI = Crown root initiation, MT = Maximum tillering, FS = Flowering stage,
AH = At harvest
Figures in parentheses are water stocks (cm)

effect of N on root volume at all the growth stages during both the years of study. There was increasing trend in root volume at each growth stage with increase in N levels from 40 to 120 kg ha^{-1}. Root volume increased significantly from 0.51 x 10^{-3}, 1.41 x 10^{-3} and 1.62 x 10^{-3} m^3m^{-3} to 0.65 x 10^{-3}, 1.82 x 10^{-3} and 2.09 x 10^{-3} m^3m^{-3} with an increase in N level from 80 to 120 kg ha^{-1} at crown root initiation, flowering and at crop harvest, respectively, during the year 1989-90. The level 120 kg N ha^{-1} showed significantly higher root volume over N_{40} (0.48 x 10^{-3}, 0.99 x 10^{-3} and 1.25 x 10^{-3} m^3m^{-3}) at these stages. At harvest 40 kg N ha^{-1} (1.40 x 10^{-3} m^3m^{-3}) and 80 kg N ha^{-1} (1.62 x 10^{-3} m^3m^{-3}) levels were at par with each other. At maximum tillering stage N_{120} produced significantly higher root volume (1.26 x 10^{-3} m^3m^{-3}) over N_{40} (0.99 x 10^{-3} m^3m^{-3}), but the increase with N levels was not significant. During the second year of study, root volume increased from 0.51 x $10^{-3}m^3m^{-3}$ at N_{40} to 0.72 x 10^{-3} m^3m^{-3} at N_{120} at crown root initiation. But the significant increase with N levels was from 0.52 x 10^{-3} m^3m^{-3} (N_{80}) to 0.72 x 10^{-3} m^3m^{-3} (N_{120}). At maximum tillering and at crop harvest root volume increased significantly from 0.72 x 10^{-3} and 0.98 x 10^{-3} m^3m^{-3} to 0.94 x 10^{-3} and 1.44 x 10^{-3} m^3m^{-3}, respectively with increase in N from 40 to 80 kg ha^{-1}. It further increased to 1.08 x 10^{-3} and 1.70 x 10^{-3} m^3m^{-3} at N_{120} at these stages, but the increase was not significant. At third stage, i.e. flowering, N_{120} exhibited significantly higher root volume of 1.66 x 10^{-3} m^3m^{-3} over N_{40} of 0.95 x 10^{-3} m^3m^{-3}, but increase with N levels was not significant.

The effect of tillage methods on root volume (Table 8) at crown root initiation and maximum tillering during 1989-90 and at all the growth stages during the year 1990-91 was not significant. Root volume increased significantly from 1.39 x 10^{-3} and 1.61 x 10^{-3} m^3m^{-3} (T_1) to 1.60 x 10^{-3} and 1.30 x 10^{-3} m^3m^{-3} (T_2) at flowering stage and at crop harvest, respectively during the year 1989-90. At crown root initiation and maximum tillering, root volume increased from 0.52 x 10^{-3} and 1.07 x 10^{-3} m^3m^{-3} (T_1) to 0.56 x 10^3 and 1.18 x 10^{-3} m^3m^{-3} (T_2), respectively, but the increase was not significant. Similarly, during the second year of study, root volume at crown root initiation, maximum tillering, flowering and at crop harvest increased from 0.55 x 10^{-3}, 0.89 x 10^{-3}, 1.22 x 10^{-3} and 1.26 x 10^{-3} m^3m^{-3} (T_1) to 0.62 x 10^{-3}, 0.94 x 10^{-3}, 1.40 x 10^{-3} and 1.48 x 10^{-3} m^3m^{-3} (T_2), respectively.

There was no significant effect of water stocks on root volume (Table 8) at any growth stage during the year 1989-90. Since the water stocks during the year 1990-91 were not variable, the data on root volume were not recorded.

In general, it was observed that with the advancement in age of the crop, the increase in root volume was more from crown root initiation to maximum tillering than from maximum tillering to flowering. The increases being 0.51 x 10^{-3}, 0.61 x 10^{-3} and 0.61 x 10^{-3} m^3m^{-3} from crown root initiation to maximum tillering and 0.26 x 10^{-3}, 0.29 x 10^{-3} and 0.56 x 10^{-3} m^3m^{-3} from maximum tillering to flowering at N_{40}, N_{80} and N_{120}, respectively during the first year of study. The corresponding increases during the second year were 0.21 x 10^{-3}, 0.42 x 10^{-3} and 0.36 x 10^{-3} m^3m^{-3}; 0.23 x 10^{-3}, 0.24 x 10^{-3} and 0.58 x 10^{-3} m^3m^{-3}. Under tillage methods, T_1 and T_2, the increases were 0.55 x 10^{-3} and 0.62 x 10^{-3} m^3m^{-3} from crown root initiation to maximum tillering; 0.32 x 10^{-3} and 0.42 x 10^{-3} m^3m^{-3} from maximum tillering to flowering, respectively, during the year 1989-90. The corresponding increase for the second year of study were 0.34 x 10^{-3} and 0.32 x 10^{-3} m^3m^{-3}; 0.33 x 10^{-3} and 0.46 x 10^{-3} m^3m^{-3}. The increases under the water stocks W_1, W_2 and W_3 were 0.38 x 10^{-3}, 0.41 x 10^{-3} and 0.33 x 10^{-3} m^3m^{-3}, from maximum tillering to flowering, respectively. The root volume, except crown root initiation stage, was higher under both N levels and tillage methods during the year 1989-90 in comparison to 1990-91.

4.5.3 Root Length Density

The data depicting the influence of different levels of N, tillage methods and water stocks on root length density (RLD) in the 0-30 cm depth at important growth stages, viz., crown root initiation, maximum tillering, flowering and at crop harvest are presented in Table 9 for the years 1989-90 and 1990-91.

A perusal of the data (Table 9) indicates that there was significant influence of N on RLD at different stages of growth during both the years of study. There was increasing

Table 9: Effect of nitrogen levels, tillage methods and water stocks on root length density ($m^3 m^{-3} x 10^4$) at different stages and harvest of wheat crop

Treatments	1939-90				1990-91			
	Stages of wheat growth							
	CRI	MT	FS	AH	CRI	MT	FS	AH
Nitrogen levels (N)								
N_{40}	0.15	0.27	0.35	0.39	0.12	0.33	0.38	0.39
N_{80}	0.17	0.33	0.42	0.49	0.14	0.41	0.45	0.54
N_{120}	0.26	0.42	0.49	0.55	0.24	0.46	0.61	0.57
CD 0.05	0.06	0.06	0.06	0.04	0.08	0.08	0.04	0.03
Tillage methods (T)								
T_1	0.18	0.31	0.41	0.46	0.17	0.38	0.43	0.47
T_2	0.20	0.37	0.44	0.49	0.17	0.41	0.52	0.53
CD 0.05	NS	0.03	NS	NS	NS	NS	NS	NS
Water stocks (W)								
W_1		0.34 (35.0)	0.40 (31.2)	0.46 (30.7)				
W_2		0.34 (36.4)	0.43 (30.8)	0.46 (30.1)				
W_3		0.32 (37.3)	0.48 (31.1)	0.52 (31.0)				
CD 0.05		NS	NS	NS				

CRI=Crown root initiation, MT=Maximum tillering, FS=Flowering stage, AH=At harvest

Figures in parentheses are water stocks (cm)

trend in RLD at each growth stage with increase in N from 40 to 120 kg ha^{-1}. Root length density increased significantly from 0.17 x 10^4 and 0.33 x 10^4 m^3m^{-3} to 0.26 x 10^4 and 0.42 x 10^4 m^3m^{-3} at crown root initiation and maximum tillering stages, respectively with increase in N level from 80 to 120 kg ha^{-1} during the year 1989-90. At crown root initiation N_{120} (0.26 x 10^4 m^3m^{-3}) showed significantly higher RLD over N_{40} (0.15 x 10^4 m^3m^{-3}) and at maximum tillering N_{40} (0.27 x 10^4 m^3m^{-3}) and N_{80} (0.33 x 10^4 m^3m^{-3}) were at par with each other. In the year 1989-90 the RLD at flowering and at crop harvest significantly increased from 0.35 x 10^4 and 0.39 x 10^4 m^3m^{-3} to 0.49 x 10^4 and 0.55 x 10^4 m^3m^{-3}, respectively with increase in N level from 40 to 120 kg ha^{-1}. During the second year of study the RLD at crown root initiation increased significantly from 0.12 x 10^4 m^3m^{-3} at N_{40} to 0.24 x 10^4 m^3m^{-3} at N_{120}. The increase in N level from 80 to 120 kg ha^{-1} increased RLD from 0.14 x 10^4 m^3m^{-3} to 0.24 x 10^4 m^3m^{-3}. At maximum tillering N_{120} gave significantly higher RLD (0.46 x 10^4 m^3m^{-3}) over N_{40} of 0.33 x 10^4 m^3m^{-3}, but N_{40} and N_{80} (0.41 x 10^4 m^3m^{-3}) were at par with each other. Root length density at flowering significantly increased from 0.38 x 10^4 m^3m^{-3} at N_{40} to 0.61 x 10^4 m^3m^{-3} at N_{120} with the increase in N levels, whereas, at crop harvest the significant increase was only from 0.39 x 10^4 m^3m^{-3} at N_{40} to 0.54 x $10^4m^3m^{-3}$ at N_{80}. But N_{80} (0.54 x 10^4 m^3m^{-3}) and N_{120} (0.57 x 10^4 m^3m^{-3}) were at par with each other.

The effect of tillage methods on RLD (Table 9) was not significant at any growth stage during both the years of study except maximum tillering stage during the year 1989-90, where it increased significantly. The trend in RLD was increasing at all the growth stages and increased from 0.18×10^4, 0.31×10^4, 0.41×10^4 and 0.46×10^4 m^3m^{-3} at T_1 to 0.20×10^4, 0.37×10^4, 0.44×10^4 and 0.49×10^4 m^3m^{-3} at T_2 at crown root initiation, maximum tillering, flowering and at crop harvest, respectively. The corresponding values for the second year were 0.17×10^4, 0.38×10^4, 0.43×10^4 and 0.47×10^4 m^3m^{-3} at T_1 and 0.17×10^4, 0.41×10^4, 0.52×10^4 and 0.53×10^4 m^3m^{-3} at T_2 method of tillage.

The water stocks did not reflect their effect on RLD (Table 9) at any growth stage, but it increased from 0.41×10^4 and 0.46×10^4 m^3m^{-3} (W_1) to 0.49×10^4 and 0.52×10^4 m^3m^{-3} (W_3) at flowering and at crop harvest, respectively. At maximum tillering and at crop harvest, W_1 and W_2 showed equal values of RLD being 0.34×10^4 and 0.46×10^4 m^3m^{-3}, respectively. At maximum tillering, however, it decreased to 0.32×10^4 m^3m^{-3} at W_3 level of water stock. During the year 1990-91, the data on RLD were not recorded.

In general, the RLD under N levels and tillage methods at crown root initiation was more during 1989-90, whereas, at other crop growth stages and at crop harvest it was more during 1990-91 (Table 9). The increase in RLD was more from crown root initiation to maximum tillering than from maximum tillering to flowering. The increases were 0.12×10^4, 0.16×10^4 and 0.16×10^4 m^3m^{-3} from crown root initiation to maximum tillering and 0.03×10^4, 0.09×10^4 and 0.07×10^4 m^3m^{-3} from maximum tillering to flowering at N_{40}, N_{80} and N_{120}, respectively, during the first year of study. The corresponding increases during these stages for the year 1990-91 were 0.21×10^4, 0.27×10^4 and 0.22×10^4 m^3m^{-3}; 0.05×10^4, 0.04×10^4 and 0.15×10^4 m^3m^{-3}. The increases under the tillage methods, T_1 and T_2, from crown root initiation to maximum tillering and maximum tillering to flowering were 0.13×10^4 and 0.17×10^4 m^3m^{-3}; 0.05×10^4 and 0.05×10^4 m^3m^{-3} for the first year of study, 0.21×10^4 and 0.24×10^4 m^3m^{-3}; 0.05×10^4 and 0.11×10^4 m^3m^{-3} for the second year of study, respectively. The increases under the water stocks W_1, W_2 and W_3 were 0.06×10^4, 0.09×10^4 and 0.17×10^4 m^3m^{-3}, respectively, from maximum tillering to flowering stage.

4.6 Evaluation of Crop Water Stress

The crop water stress indices viz., relative leaf water content (RLWC), xylem water potential (XWP), leaf diffusion resistance (LDR) and stress degree days (SDD), recorded at different stages of wheat growth, are presented in Tables 10, 11, 12 and Fig.10 (a, b).

4.6.1 Relative Leaf Water Content

The relative leaf water content determined at maximum tillering and flowering stages of wheat growth during the years

1989-90 and 1990-91 is presented in Table 10. A perusal of the data indicates that the RLWC was significantly affected by N levels at maximum tillering and flowering stages during the year 1989-90. Relative leaf water content increased significantly from 73.9 per cent to 80.6 per cent with increase in N level from 40 to 120 kg ha^{-1} at maximum tillering, but at flowering stage the increase was from 72.4 per cent at N_{40} to 77.8 per cent at N_{80}. The levels 80 and 120 kg N ha^{-1} showed equal value of RLWC (77.8%) at flowering during the first year of study. Relative leaf water content increased from 79.8 and 71.5 per cent to 82.7 and 75.9 per cent with increase in N level from 40 to 120 kg ha^{-1} at maximum tillering and flowering stages, respectively, during the second year of study, but the significant increase was only at flowering stage.

The influence of tillage methods on RLWC (Table 10) was significant only at maximum tillering stage during 1989-90. Relative leaf water content increased from 76.8 and 75.5 per cent at T_1 to 78.2 and 76.3 per cent at T_2 at maximum tillering and flowering stages, respectively, during the year 1989-90. The corresponding values for the year 1990-91 were 81.1 and 73.2 per cent at T_1 and 81.2 and 73.9 per cent at T_2.

There was no significant effect of water stocks on RLWC (Table 10) at both the growth stages during the first year of study. During second year of study, the data on RLWC were not recorded.

Table 10: Effect of nitrogen levels, tillage methods and water stocks on relative leaf water content (%) at different stages of wheat growth

Treatments	1989-90		1990-91	
	Stages of wheat growth			
	MT	FS	MT	FS
Nitrogen levels (N)				
N_{40}	73.9	72.4	79.8	71.5
N_{80}	78.0	77.8	80.8	73.3
N_{120}	80.6	77.8	82.7	75.9
CD 0.05	1.7	3.5	NS	1.3
Tillage methods (T)				
T_1	76.8	75.5	81.1	73.2
T_2	78.2	76.3	81.2	73.9
CD 0.05	1.4	NS	NS	NS
Water stocks (W)				
W_1	76.7 (35.0)	74.3 (31.2)		
W_2	76.5 (36.4)	76.7 (30.8)		
W_3	77.3 (37.3)	76.6 (31.1)		
CD 0.05	NS	NS		

MT=Maximum tillering, FS=Flowering stage

Figures in parentheses are water stocks (cm)

A comparison of results for the year 1989-90 (Table 10) at different growth stages reveals that N_{120} maintained higher RLWC (80.6 and 77.8%) over N_{40} (73.9 and 72.4%) and T_2 maintained higher RLWC (78.2 and 76.3%) over T_1 (76.8 and 75.5%) at maximum tillering and flowering stages, respectively. Whereas, during the year 1990-91 the corresponding RLWC values at N_{120} were 82.7 and 75.9 per cent; at N_{40} being 79.8 and 71.5 per cent. Under tillage methods the RLWC values were 81.2 and 73.9 per cent at T_2, and 81.1 and 73.2 per cent at T_1. The RLWC was higher at maximum tillering than at flowering stage during both the years of study. It decreased with time and the decreases were 2.1, 0.3 and 3.6 per cent during 1989-90 and 11.7, 10.2 and 9.0 per cent during 1990-91 from maximum tillering to flowering at N_{40}, N_{80} and N_{120}, respectively. The corresponding decreases under tillage methods, T_1 and T_2, were 1.7 and 2.5 per cent during 1989-90; 10.8 and 9.9 per cent during 1990-91. The decrease with time was very small during the year 1989-90, both under N levels and tillage methods, in comparison to the year 1990-91.

4.6.2 Xylem Water Potential

The influence of N levels, tillage methods and water stocks on xylem water potential (XWP) recorded at three important growth stages of wheat, viz., crown root initiation, maximum tillering and flowering during the years 1989-90 and 1990-91 is shown in Table 11a. A perusal of the data indicates

Table 11a: Effect of nitrogen levels, tillage methods and water stocks on xylem water potential (-bar) at different stages of wheat growth

Treatments	1989-90			1990-91		
	Stages of wheat growth					
	CRI	MT	FS	CRI	MT	FS
Nitrogen levels (N)						
N_{40}	10.6	12.9	17.9	5.1	17.1	18.0
N_{80}	9.3	12.6	17.0	4.7	16.1	16.8
N_{120}	8.6	12.2	15.7	4.8	16.4	16.4
CD 0.05	0.8	0.5	0.8	NS	NS	0.6
Tillage methods (T)						
T_1	0.5	12.9	17.3	4.9	16.9	17.0
T_2	9.4	12.3	16.5	4.8	16.1	16.5
CD 0.05	NS	0.4	0.7	NS	NS	NS
Water stocks (W)						
W_1		12.8 (35.0)	17.4 (31.2)			
W_2		12.6 (36.4)	17.2 (30.8)			
W_3		12.7 (37.3)	16.8 (31.1)			
CD 0.05		NS	NS			

CRI = Crown root initiation, MT = Maximum tillering, FS = Flowering stage

Figures in parentheses are water stocks (cm)

that there was significant effect of N on XWP at all the growth stages during the year 1989-90, but only at flowering stage during the year 1990-91. At crown root initiation XWP increased significantly from -10.6 to -9.3 bar with increase in N level from 40 to 80 kg ha^{-1}. It further increased to -8.6 bar at 120 kg N ha^{-1}, but the increase was not significant. At second stage, i.e. maximum tillering, there was increasing trend in XWP with increase in N level from 40 to 120 kg ha^{-1}, but the increase with N levels was not significant. However, N_{120} (-12.2 bar) showed significantly higher XWP over N_{40} (12.9 bar). At flowering, XWP increased significantly from -17.9 to -15.7 bar with increase in N from 40 to 120 kg ha^{-1}. During the second year of study XWP at crown root initiation stage increased from -5.1 at N_{40} to -4.7 bar at N_{80} then decreased to -4.8 bar at N_{120}, but there was no significant effect of N levels. Similar trend was observed at maximum tillering, where XWP increased from -17.1 bar at N_{40} to -16.1 bar at N_{80}, then decreased to -16.4 bar at N_{120}. At flowering stage, XWP increased significantly from -18.0 bar at N_{40} to -16.4 bar at N_{120}.

Xylem water potential increased under tillage methods, T_1 and T_2, at every stage (Table 11a) during both the years of study, but the significant effect was only at maximum tillering and flowering stages during 1989-90. Xylem water potential (XWP) increased from -9.5, -12.9 and -17.3 bar (T_1) to -9.4, -12.3 and -16.5 bar (T_2) at crown root initiation, maximum tillering and flowering stages, respectively, during the year 1989-90. The corresponding XWP values for the year 1990-91 were -4.9, -16.9 and -17.0 bar at T_1 and -4.8, -16.1 and -16.5 bar at T_2.

The interaction NxT was found significant at crown root initiation stage during the first year of study (Table 11b).

Table 11b: Interaction effect of nitrogen levels and tillage methods on xylem water potential (-bar) at crown root initiation stage of wheat growth

Tillage methods		Nitrogen levels		
		N_{40}	N_{80}	N_{120}
T_1		10.7	9.3	8.6
T_2		10.4	9.2	8.5
CD 0.05	1.1			

A perusal of the data (Table 11b) indicates that both under T_1 and T_2, XWP increased significantly from -10.7 and -10.4 bar at N_{40} to -9.3 and -9.2 bar at N_{80}, respectively. It further increased to -8.6 and -8.5 bar at N_{120}, but the increase was not significant. Under N levels, T_2 always showed higher value of XWP than T_1, but did not differ significantly. The treatment $N_{120}T_2$ showed significantly higher XWP over the treatments $N_{40}T_1$ and $N_{40}T_2$.

There was no significant effect of water stocks on XWP (Table 11a) during the year 1989-90. During the second year (1990-91), the observations on XWP were not recorded.

A comparison of results for the XWP at different growth stages during the two years of study (Table 11a) reveals that its status was low at crown root initiation during the year

1989-90, but was high at maximum tillering stage in comparison to 1990-91. At flowering stage the XWP was almost same or comparable during two years of study. There was reduction in XWP with age of crop. For example, as the crop advanced from crown root initiation to maximum tillering and maximum tillering to flowering the reductions in XWP during the year 1989-90 were 2.3, 3.3 and 3.6 bar, and 5.0, 4.4 and 3.5 bar at N_{40}, N_{80} and N_{120}, respectively. The corresponding reductions for the year 1990-91 were 12.0, 11.4 and 11.6 bar, and 0.9, 1.0 and 0.0 bar. Under tillage methods, T_1 and T_2, the reductions were 3.4, 2.9 bar from crown root initiation to maximum tillering, 4.4 and 4.2 bar from maximum tillering to flowering, respectively during the year 1989-90. The corresponding reductions for the year 1990-91 were 12.0 and 11.3 bar; 0.1 and 0.4 bar. Under water stocks W_1, W_2 and W_3, the reductions were 4.6, 4.6 and 4.1 bar, respectively from maximum tillering to flowering. The level 120 N kg ha^{-1} maintained 18.9, 5.4 and 12.3 per cent higher XWP over N_{40} during the year 1989-90; 5.9, 4.1 and 8.9 per cent during the year 1990-91 at crown root initiation, maximum tillering and flowering stages, respectively. Similarly, T_2 maintained 1.1, 4.7 and 4.6 per cent higher XWP over T_1 during 1989-90 and 2.9, 4.7 and 2.9 per cent during 1990-91 at crown root initiation, maximum tillering and flowering stages, respectively. Under water stocks, W_2 maintained 1.6 and 0.01 per cent higher XWP over W_1 and W_3, respectively at maximum tillering, whereas W_3 showed 3.4 per cent higher XWP over W_1 at flowering stage.

4.6.3 Diurnal Changes in Xylem Water Potential

The diurnal changes in XWP from 0800 to 1700h under different levels of N, tillage methods and water stocks at flowering stage of wheat growth for the years 1989-90 and 1990-91 are depicted in Figs. 8(a,b,c) and 9(a,b).

4.6.3.1 Diurnal Changes in XWP under N levels: The diurnal changes in XWP under different levels of N at flowering stage of wheat growth are depicted in Fig. 8a for the year 1989-90. A perusal of the figure reveals that at 0800h, XWP under different levels of N was equal and maximum (-11.7 bar). At 1100h it decreased rapidly with time and reached the values of -16.9, -15.3 and -15.2 bar under N_{40}, N_{80} and N_{120}, respectively. For N_{40} level the XWP remained minimum (-16.9 bar) from 1100 to 1300h, whereas for N_{80} and N_{120} levels it steadily decreased until 1300h, and attained minimum values of -16.4 and -15.9 bar, respectively. Beyond 1300h XWP started recovering and reached the maximum values of -13.7, -13.6 and -12.9 bar under N_{40}, N_{80} and N_{120}, respectively at 1700h.

The second year of crop study (Fig. 9a) reveals that XWP under different levels of N at 0800h was quite high (-6.7 bar) and beyond this period XWP decreased very rapidly till 1300h and reached the minimum values of -17.2, -16.4 and -16.0 bar under N_{40}, N_{80} and N_{120}, respectively. It recovered slowly until 1500h, but after that it increased with a rapid rate and attained maximum values of -11.3, -11.2 and -11.7 bar at 1700 h for N_{40}, N_{80} and N_{120} levels, respectively.

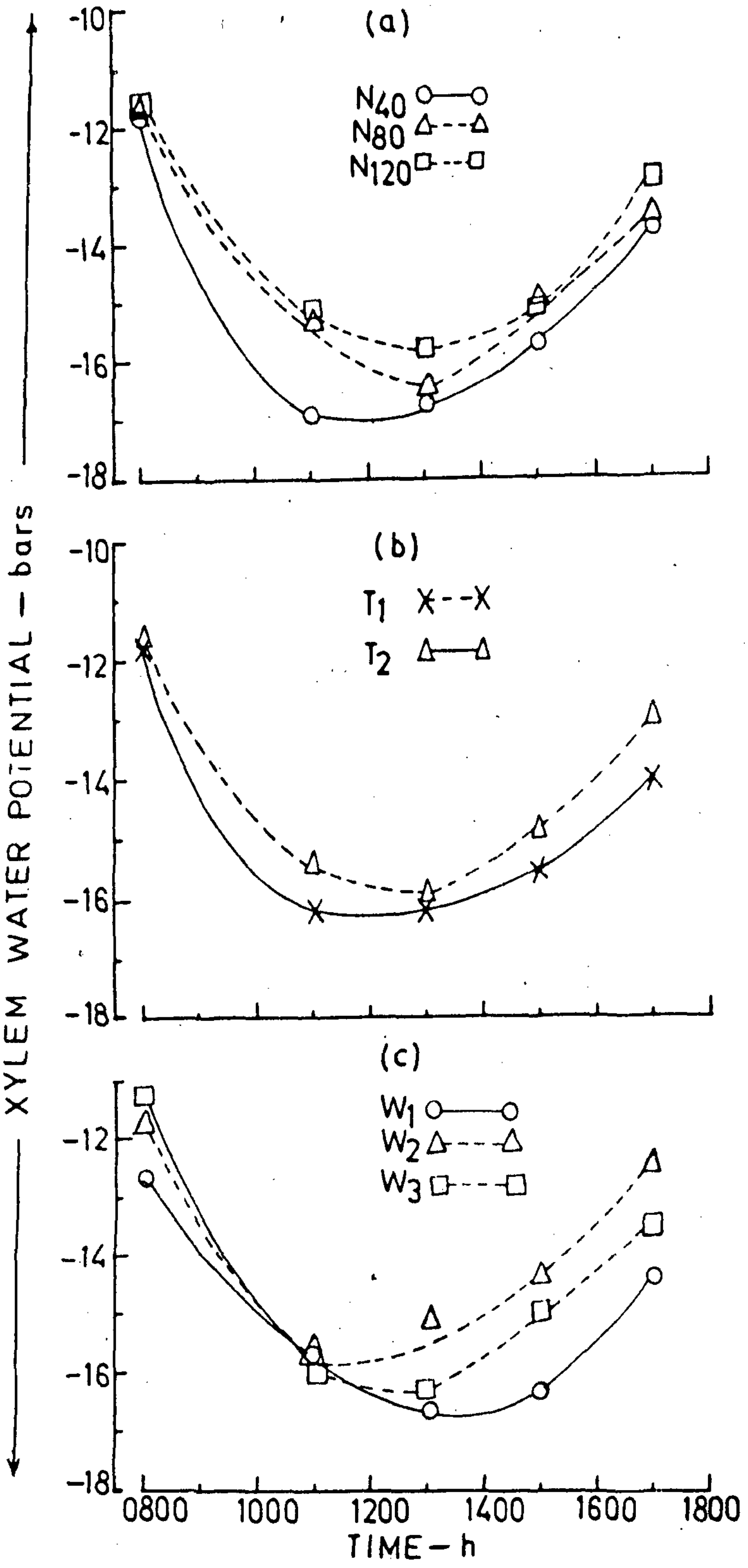


Fig.8 Diurnal changes in xylem water potential of wheat at flowering stage during the year 1989-90 under (a) nitrogen levels (b) tillage methods, (c) water stocks

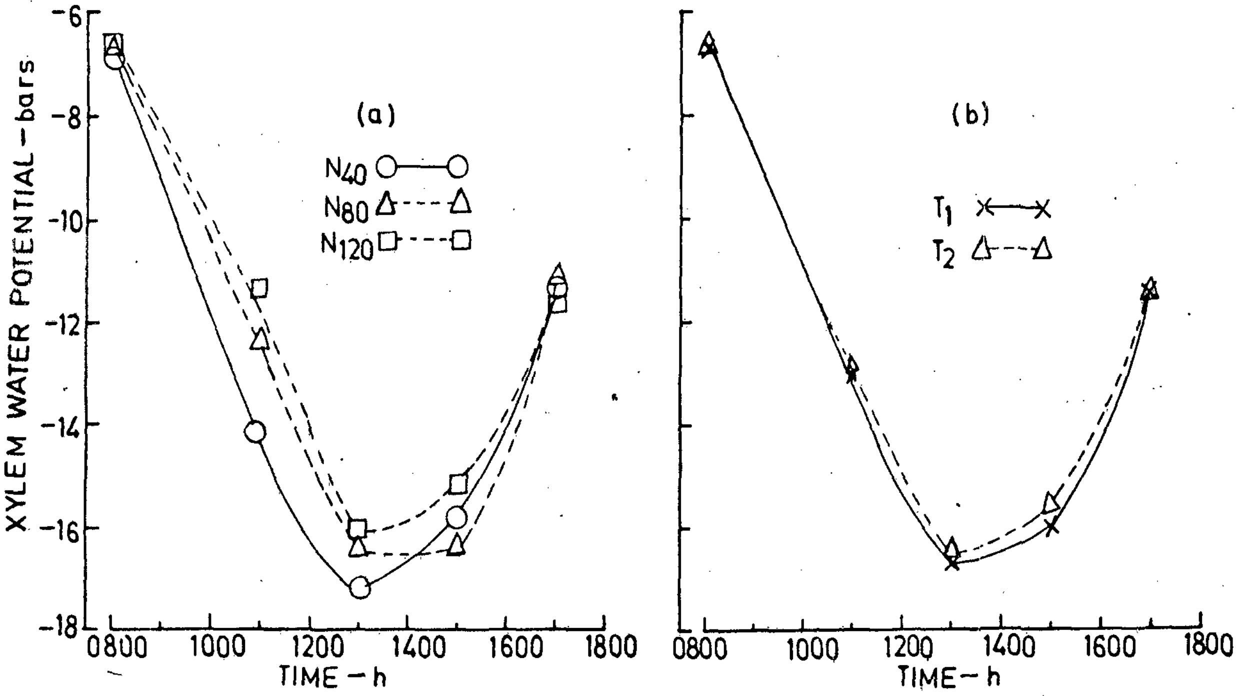


Fig.9 Diurnal changes in xylem water potential of wheat at flowering stage during the year 1990-91 under (a) nitrogen levels (b) tillage methods

4.6.3.2 Diurnal changes in XWP under Tillage Methods: The diurnal changes in XWP under tillage methods, T_1 and T_2, at flowering stage of wheat growth during the years 1989-90 and 1990-91 are depicted in Fig. 8b and 9b. A perusal of the Fig. 8b reveals that the XWP at 0800h under tillage methods, T_1 and T_2, was equal and maximum, being -11.7 bar. At 1100h it decreased rapidly with time and reached the values of -16.2 and -15.4 bar under T_1 and T_2, respectively. It remained constant (-16.2 bar) from 1100 to 1300h under T_1, but decreased to -16 bar under T_2. Beyond 1300h it started recovering and reached the maximum values of -14.0 and -13.0 bar under T_1 and T_2, respectively at 1700h.

The second year of study (Fig.9b) reveals that XWP under different tillage methods at 0800h was quite high (-6.7 bar). It decreased rapidly with time and reached the values of -13.2 and -13.0 bar under T_1 and T_2 at 1100h, but it further decreased and reached the minimum values of -16.7 and -16.5 bar under T_1 and T_2, respectively, at 1300h. Beyond this, it started recovering and attained the maximum value of -11.4 under T_1 and T_2 at 1700h.

4.6.3.3 Diurnal Changes in XWP under Water Stocks: The diurnal changes in XWP under the water stocks at flowering stage of wheat growth during the year 1989-90 are depicted in Fig.8c. A perusal of figure reveals that XWP was quite high at 0800h, being -12.7, -11.7 and -11.2 bar under W_1, W_2 and W_3, respectively. It decreased with time rapidly till 1100h and reached the values of -15.7, -15.8 and -16.0 bar, it further decreased, but at a slower rate and attained the minimum values of -16.6, -15.6 and -16.4 bar under W_1, W_2 and W_3, respectively at 1300h. Thereafter, it started recovering and reached the values of -14.4, -12.3 and -13.5 bar under W_1, W_2 and W_3, respectively at 1700h. Since the water stocks during the year 1990-91 were not variable, hence the data on XWP were not recorded.

In general, it was observed that during the first year of study the XWP at 0800h was quite low in comparison to the second year, both under N levels and tillage methods. The reduction beyond 0800h was slow during 1989-90 in comparison to 1990-91. The mid-day values of XWP both under N levels and tillage methods, were comparable for the two years of study. The values attained at 1700h after the recovery were low during 1989-90 in comparison to the year 1990-91. At 1700h the values of XWP were quite low than the values at 0800h both under N levels and tillage methods during both the years of study. With respect to water stocks, the W_2 maintained higher XWP than W_1 and W_3 at 0800h, but during the mid-day (1300h) W_1 maintained XWP status lower than the W_2 and W_3, but W_2 maintained XWP higher than W_3. Similarly, at 1700h the XWP under W_1 water stock was lower than the values at W_2 and W_3.

4.6.4 Leaf Diffusion Resistance

Leaf diffusion resistance (LDR) determined at maximum tillering and flowering stages of wheat growth during the years

1989-90 and 1990-91 is shown in Table 12. A perusal of the data indicates that there was significant effect of N on LDR at both the stages in the year 1989-90, but only at flowering stage during the year 1990-91. During the first year of study LDR at maximum tillering stage decreased significantly from 3.06 to 2.40 s cm^{-1} with increase in N level from 40 to 80 kg ha^{-1}, but not significantly. Similarly at flowering stage LDR drcreased significantly from 4.25 to 3.25 s $cm^{-1}$with increase in N from 80 to 120 kg ha^{-1}. The level 120 kg N ha^{-1} showed significantly lower LDR in comparison to the value of 4.53 s cm^{-1} under 40 kg N ha^{-1} treatment. The second year of study reflected no effect of N on LDR at maximum tillering stage, but it decreased from 2.12 to 1.84 s cm^{-1} with increase in N from 40 to 120 kg ha^{-1}. At flowering N_{120} showed significantly low LDR (2.83 s cm^{-1}) over N_{40} (3.75 s cm^{-1}), but values were at par under N_{40} and N_{80} (3.06 s cm^{-1}) treatments.

Leaf diffusion resistance was significantly affected by tillage methods at flowering stage (1989-90), but there was no significant effect at both the growth stages during the second year of study (Table 12). Deep ploughing (T_2) always showed lower value of LDR over conventional tillage (T_1) at each growth stage during both the years of study. The LDR values were 2.31 and 3.77 s cm^{-1} at T_2, 2.75 and 4.25 s cm^{-1} at T_1 at maximum tillering and flowering stages, respectively during the year 1989-90. The corresponding values for the second year of study were 1.84 and 3.05 s cm^{-1}; 2.09 and 3.47 s cm^{-1}.

Table 12: Effect of nitrogen levels, tillage methods and water stocks on leaf diffusion resistance (s cm^{-1}) at different stages of wheat growth

Treatments	1989-90		1990-91	
	Stages of wheat growth			
	MT	FS	MT	FS
Nitrogen levels (N)				
N_{40}	3.06	4.53	2.12	3.75
N_{80}	2.40	4.25	1.98	3.06
N_{120}	2.12	3.25	1.84	2.83
CD 0.05	0.58	0.46	NS	0.69
Tillage methods (T)				
T_1	2.75	4.25	2.09	3.47
T_2	2.31	3.77	1.84	2.95
CD 0.05	NS	0.38	NS	NS
Water stocks (W)				
W_1	2.68 (35.0)	4.07 (31.2)		
W_2	2.39 (36.4)	4.00 (30.8)		
W_3	2.52 (37.3)	3.95 (31.1)		
CD 0.05	NS	NS		

MT = Maximum tillering, FS = Flowering stage

Figures in parentheses are water stocks (cm)

There was no significant effect of water stocks on LDR (Table 12) at both the growth stages (1989-90), but it varied from 2.68 (W_1) to 2.39 (W_2) s cm^{-1} at maximum tillering and 4.07 (W_1) to 3.95 (W_3) s cm^{-1} at flowering. Since the water stocks during the year 1990-91 were not variable, hence the data on LDR were not recorded.

Leaf diffusion resistance during 1989-90 was higher than the year 1990-91 at both the growth stages, both under N levels and tillage methods. The treatment 120 kg N ha^{-1} maintained 30.7 and 28.3 per cent; 13.2 and 24.5 per cent lower LDR over N_{40} at maximum tillering and flowering, respectively during the year 1989-90 and 1990-91. Similarly, T_2 maintained 16.0 and 11.3 per cent lower LDR over T_1 during 1989-90 at maximum tillering and flowering stages, respectively. The corresponding values for the year 1990-91 were 12.0 and 12.1 per cent.

At maximum tillering W_2 maintained 10.8 and 5.2 per cent lower LDR over W_1 and W_3, respectively, but at flowering W_3 maintained 2.9 per cent lower LDR over W_1. Leaf diffusion resistance increased with the age of crop, the increase being 1.47, 1.85 and 1.13 s cm^{-1} from maximum tillering to flowering during the year 1989-90 under N_{40}, N_{80} and N_{120}, respectively. The corresponding increase for the second year was 1.63, 1.08 and 0.99 s cm^{-1}. Similarly, under tillage methods, T_1 and T_2, the increases were 1.50 and 1.46 s cm^{-1} from maximum tillering to flowering, respectively during the first year of study. The

Corresponding values for the second year were 1.38 and 1.11 s cm^{-1}. The increases under water stocks were 1.39, 1.61 and 1.43 s cm^{-1} at W_1, W_2 and W_3, respectively from maximum tillering to flowering. Leaf diffusion resistance at both the growth stages was higher during 1989-90 than the year 1990-91.

4.6.5 Stress Degree Days

The crop canopy minus air temperature was recorded daily (except cloudy and rainy days) from 1200 to 1400h under different levels of N and tillage methods, during the growth period from 102 to 169 DAS during 1989-90 and 85 to 171 DAS during 1990-91. This period corresponds with maximum tillering, flowering and dough stages of wheat growth. The crop canopy minus air temperature difference also known as stress degree days (SDD) and its summation, the cumulative stress degree days (CSDD) were also calculated. The CSDD were plotted as a function of time under different levels of N (1989-90) and tillage methods (1989-90 and 1990-91) and depicted in Fig. 10(a,b). A glance at Fig. 10a indicates that around maximum tillering (70 to 90 DAS) there was slight difference in CSDD under different levels of N, i.e. at 90 DAS the CSDD were -3.8, 5.0 and 6.5°C at 40, 80 and 120 kg N ha^{-1}, respectively. The difference in CSDD under different levels of N increased with the age of the crop, but CSDD decreased e.g. at 110 DAS the values for CSDD were -14.5, -18.5 and -20.0°C; at 145 DAS -11.0, -21.8 and -24.0°C and at 171 DAS -18.0, -33.0 and -36.0° at 40, 80 and 120 kg N ha^{-1},

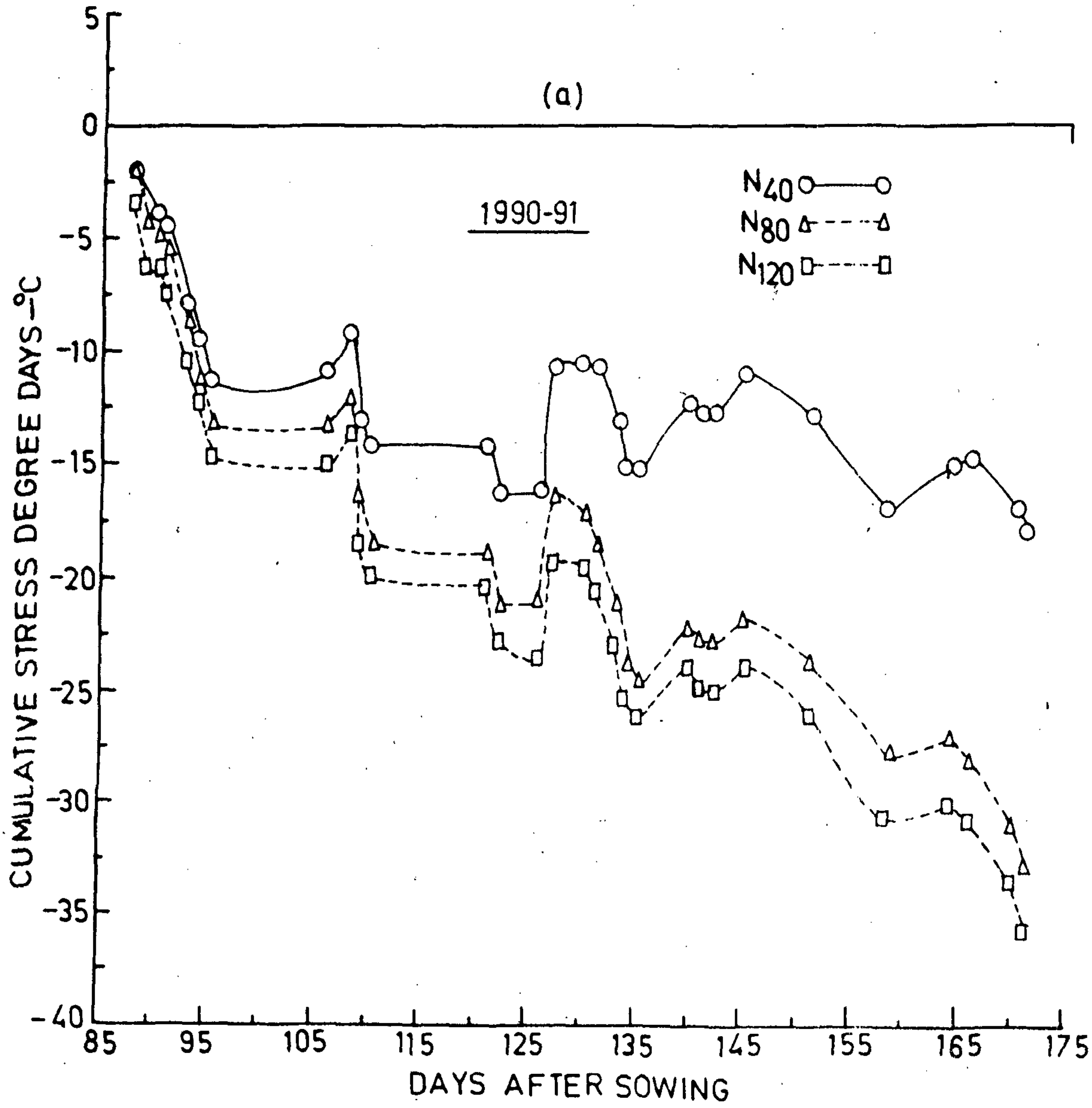
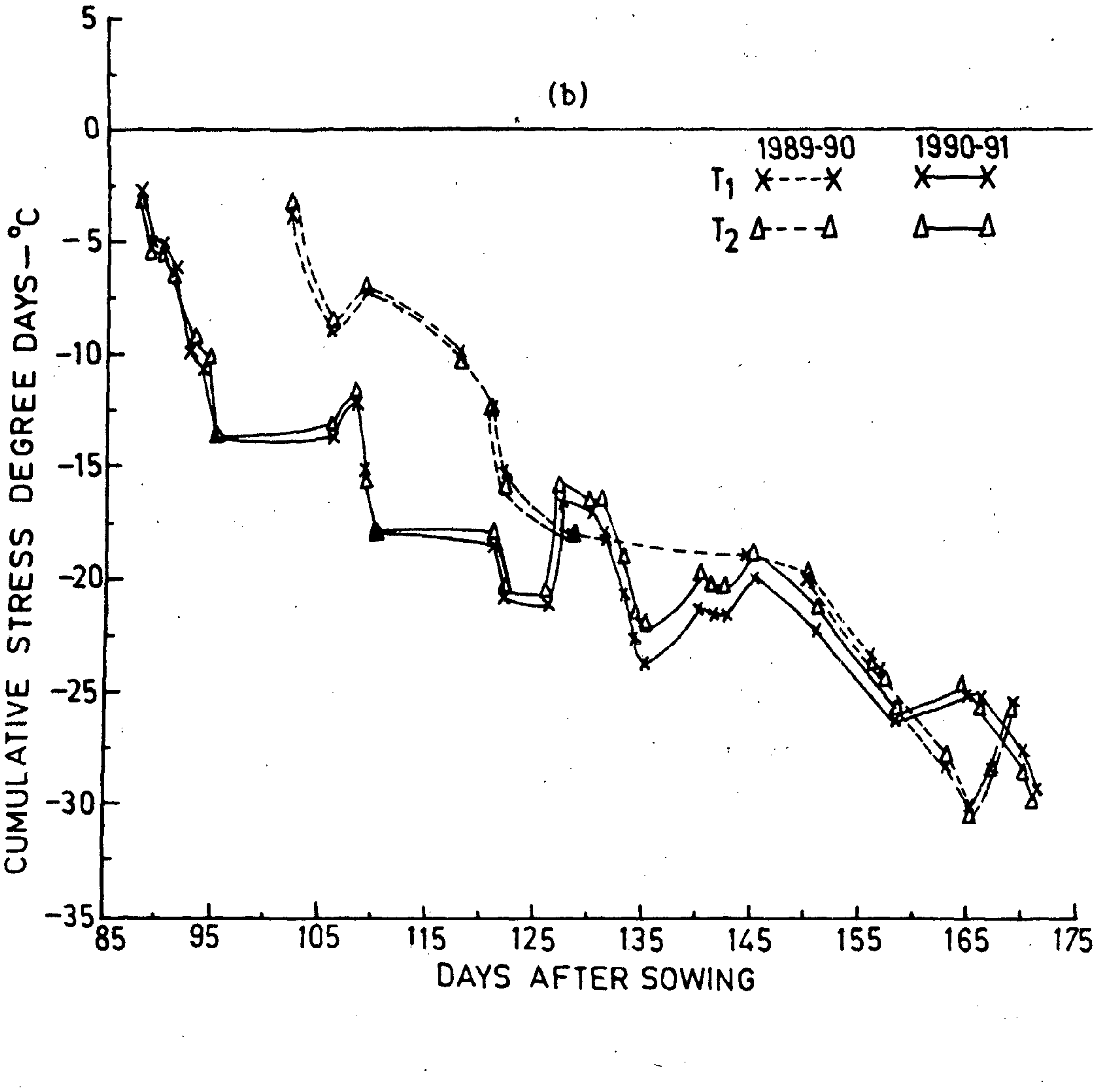


Fig.10 Cumulative stress degree days as a function of time under (a) nitrogen levels (b) tillage methods


(b)
1989-90
1990-91
T1
T2
CUMULATIVE STRESS DEGREE DAYS—°C
5
0
-5
-10
-15
-20
-25
-30
-35
85
95
105
115
125
135
145
155
165
175
DAYS AFTER SOWING

respectively. The differences in CSDD at corresponding time between N_{40} and N_{80}, N_{80} and N_{120}, and N_{40} and N_{120} were 4.0, 1.5 and 5.5°C; 10.8, 3.2 and 13.0°C, and 15.0, 3.0 and 18.0°C, respectively. The CSDD at N_{40} decreased very slightly with time, but after 122 DAS (-16.5°C) it started increasing and reached to a value of -10.5°C at 127 DAS then decreased to -15.0°C at 135 DAS and then again increased to -11.0°C (145 DAS) and again decreased to -18.0°C at 171 DAS.

The CSDD under tillage methods, as shown in Fig.10b, did not differ from each other during both the years of study but during the year 1989-90 these were higher than the values in the year 1990-91 only for a period from 102 to 127 DAS.

The variable water stocks could not be achieved in the field, hence the data on SDD and CSDD were not recorded during both the years of study.

In general, it was observed that the crop was not under moisture stress during both the years of study as the CSDD did not reach or cross the zero line of CSDD. However, within N levels the differences were quite distinct. This means that under 40 kg N ha^{-1} the crop had higher stress, i.e. higher SDD than under 80 and 120 kg N ha^{-1} levels. The crop under 80 kg N ha^{-1} level showed higher value of SDD compared to 120 kg N ha^{-1}.

4.7 Soil-Plant-Water Relations

The relationships between soil moisture storage, soil water potential with plant-water relations, viz., relative leaf water content (RLWC), xylem water potential (XWP) and leaf diffusion resistance (LDR) and among themselves at flowering stage of wheat growth are presented in Fig.11, 12 and 13, respectively.

4.7.1 Relationships Between Soil Moisture Storage and Plant-Water Status

Relationships between soil moisture storage (water stocks in 0-90 cm depth) and plant water status under different levels of N and tillage methods, at flowering stage of wheat growth are presented in Fig.11 (a,b,c) and Table 13.

4.7.1.1 Soil Moisture Storage and Relative Leaf Water Content:

A glance at Fig.11(a) reveals that RLWC was influenced by N levels and tillage methods. Under N levels, it changed from 69.5 (N_{40}) to 71.8 per cent (N_{120}) and 73.8 (N_{40}) to 84.0 per cent (N_{120}) at the lowest and the highest soil moisture storage, respectively. But with respect to tillage methods, it changed from 71.0 (T_1) to 73.2 per cent (T_2) and 82.2 (T_1) to 83.9 per cent (T_2). In general, the RLWC increased with the increase in N level, for example at soil moisture storage of 32 cm the RLWC was 72.5, 80.3 and 80.8 per cent at 40, 80 and 120 kg N ha^{-1}, respectively. Similarly, it increased under tillage methods, T_1 and T_2, the values being 79.3 and 81.0 per cent, respectively, at soil moisture storage of 32 cm. The increase in RLWC with increase in soil moisture storage was more under N levels than tillage methods.

(a)

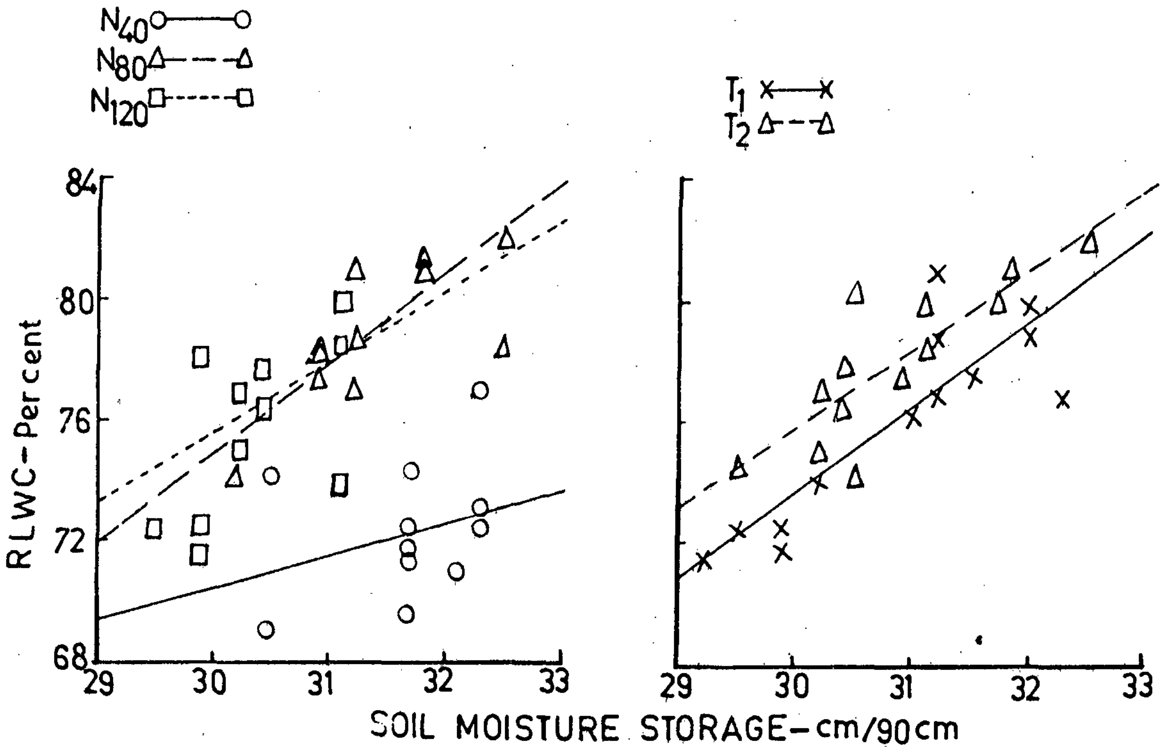


Fig.11 Relationship between soil moisture storage (SMS) and

(a) relative leaf water content (RLWC)
(b) xylem water potential (XWP) and
(c) leaf diffusion resistance (LDR) at flowering stage of wheat growth

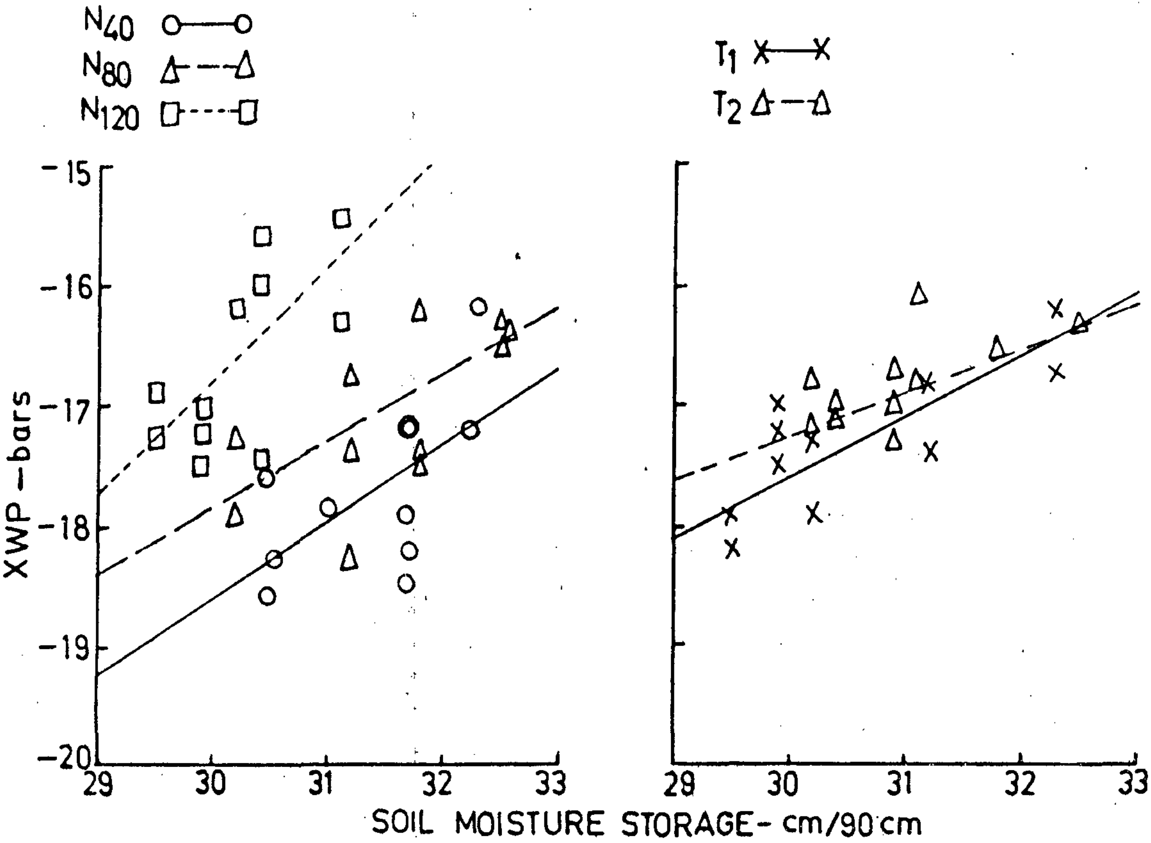
The relationship between soil moisture storage and RLWC (Table 13) was linear positive and found significant at N_{80} (r = 0.77) and under tillage methods, T_1 (r = 0.86) and T_2 (r = 0.83).

4.7.1.2 Soil Moisture Storage and Xylem Water Potential: The relationship between soil moisture storage and xylem water potential (XWP) at flowering stage of wheat growth under different levels of N and tillage methods is depicted in Fig.11(b). The XWP ranged from -19.3 to -17.8 bar and -16.8 to -13.9 bar at the lowest and the highest soil moisture storage respectively with increasing levels of N from 40 to 120 kg ha^{-1}. The XWP at the lowest value of moisture storage under tillage methods changed from -18.2 to -17.6 bar. But at the highest soil moisture storage it was almost same under both the tillage methods. The XWP was more affected by N, e.g. N_{120} maintained 1.5 and 2.9 bar higher XWP over N_{40} at the lowest and the highest soil moisture storage, respectively. The tillage method T_2 maintained 0.6 bar higher XWP over T_1 at the lowest soil moisture storage.

The relationship between soil moisture storage and XWP (Table 13) was linear, positive and found significant at N_{40}, N_{80}, N_{120}, T_1 and T_2 with coefficient of correlations of r = 0.60, 0.66, 0.64, 0.79 and 0.66, respectively.

4.7.1.3 Soil Moisture Storage and Leaf Diffusion Resistance: The relationship between soil moisture storage and LDR under N levels and tillage methods is shown in Fig.11(c). It is evident

(b)


N40 o——o
N80 Δ- - -Δ
N120 □-----□
T1 X——X
T2 Δ- -Δ
XWP - bars
-15
-16
-17
-18
-19
-20
29
30
31
32
33
SOIL MOISTURE STORAGE- cm/90 cm

(c)

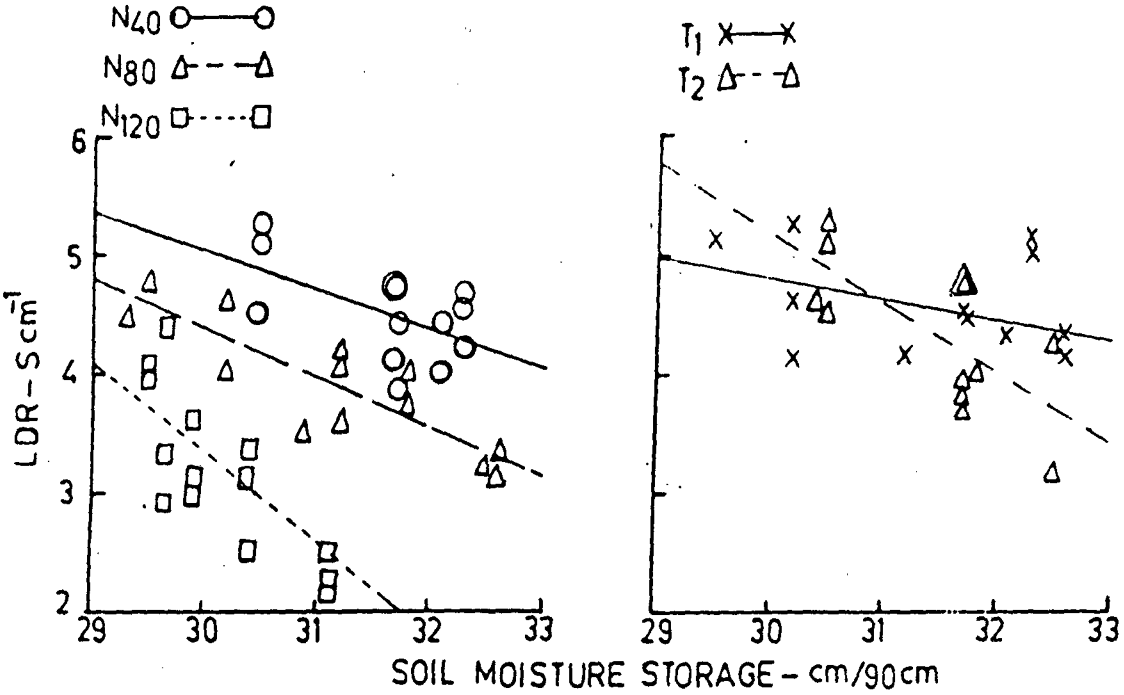

N40
N80
N120
T1
T2
LDR - S cm⁻¹
6
5
4
3
2
29
30
31
32
33
SOIL MOISTURE STORAGE - cm/90cm

Table 13: Correlation coefficients (r) for relationships between soil moisture storage (SMS) and (a) relative leaf water content (RLWC), (b) xylem water potential (XWP) and (c) leaf diffusion resistance (LDR) at flowering stage of wheat growth

		'r'	Number of observations
(a) Between soil moisture storage (SMS) and relative leaf water content (RLWC)			
N_{40}	RLWC = 37.87 + 1.09 SMS	0.30	11
N_{80}	RLWC = 5.45 + 2.34 SMS	0.71*	11
N_{120}	RLWC = -16.03 + 3.03 SMS	0.58	11
T_1	RLWC = -10.83 + 2.82 SMS	0.86*	13
T_2	RLWC = - 4.22 + 2.67 SMS	0.83*	13
(b) Between soil moisture storage (SMS) and xylem water potential (XWP)			
N_{40}	XWP = -37.57 + 0.63 SMS	0.60*	11
N_{80}	XWP = -34.34 + 0.55 SMS	0.66*	11
N_{120}	XWP = -45.62 + 0.96 SMS	0.64*	11
T_1	XWP = -32.96 + 0.51 SMS	0.79*	11
T_2	XWP = -27.77 + 0.35 SMS	0.66*	11
(c) Between soil moisture storage (SMS) and leaf diffusion resistance (LDR)			
N_{40}	LDR = 15.45 - 0.35 SMS	-0.54	13
N_{80}	LDR = 16.79 - 0.41 SMS	-0.77*	13
N_{120}	LDR = 25.82 - 0.75 SMS	-0.57*	13
T_1	LDR = 9.60 - 0.16 SMS	-0.38	12
T_2	LDR = 22.27 - 0.57 SMS	-0.71*	12

*Significant at 5 per cent level

from the figure that LDR decreased linearly with increase in soil moisture storage under N levels and tillage methods. It ranged from 5.30 (N_{40}) to 4.07 s cm^{-1} (N_{120}) and 3.90 (N_{40}) to 1.07 s cm^{-1} (N_{120}) at the lowest and the highest values of soil moisture storage, respectively, under N levels. Under tillage methods, at corresponding soil moisture storage, LDR ranged from 4.96 (T_1) to 5.74 s cm^{-1} (T_2) and 4.32 (T_1) to 3.46 s cm^{-1} (T_2). Leaf diffusion resistance decreased with increase in N levels. For example, at soil moisture storage of 31 cm, the LDR was 4.60, 4.08 and 2.57 s cm^{-1} at N_{40}, N_{80} and N_{120}, respectively. But under tillage methods the LDR was equal at this soil moisture storage. However, at soil moisture storage value above 31 cm, the LDR was lower under T_2 than T_1. However, the relationship was not discernible under tillage methods.

The relationship between soil moisture storage and LDR (Table 13) was linear, negative and found significant for N_{80}, N_{120} and T_2 with 'r' values of 0.77, 0.57 and 0.71, respectively.

4.7.2 Relationships Between Soil Water Potential and Plant Water Status

Relationships between soil water potential (average of soil water potential from 0 to 90 cm depth) and plant water status under different levels of N and tillage methods at flowering stage of wheat growth are presented in Fig.12 (a,b,c) and Table 14.

Table 14: Correlation coefficients (r) for relationship between soil water potential (SWP) and (a) relative leaf water content (RLWC), (b) xylem water potential (XWP) and (c) leaf diffusion resistance (LDR) at flowering stage of wheat growth

		'r'	Number of observations
(a) Between soil water potential (SWP) and relative leaf water content (RLWC)			
N_{40}	RLWC = 79.18 + 0.044 SWP	0.72*	10
N_{80}	RLWC = 84.11 + 0.060 SWP	0.76*	10
N_{120}	RLWC = 84.59 + 0.040 SWP	0.53	10
T_1	RLWC = 84.53 + 0.059 SWP	0.58*	17
T_2	RLWC = 85.95 + 0.050 SWP	0.42	17
(b) Between soil water potential (SWP) and xylem water potential (XWP)			
N_{40}	XWP = -16.31 + 0.015 SWP	0.85*	11
N_{80}	XWP = -16.01 + 0.010 SWP	0.65*	11
N_{120}	XWP = -13.05 + 0.025 SWP	0.77*	11
T_1	XWP = -15.83 + 0.012 SWP	0.42	16
T_2	XWP = -12.94 + 0.022 SWP	0.64*	16
(c) Between soil water potential (SWP) and leaf diffusion resistance (LDR)			
N_{40}	LDR = 3.71 - 0.005 SWP	-0.34	11
N_{80}	LDR = 2.89 - 0.008 SWP	-0.35	11
N_{120}	LDR = 1.99 - 0.008 SWP	-0.62*	11
T_1	LDR = 3.39 - 0.006 SWP	-0.44	14
T_2	LDR = 1.70 - 0.012 SWP	-0.55*	14

*Significant at 5 per cent level

4.7.2.1 Soil Water Potential and Relative Leaf Water Content: The relationship between soil water potential and RLWC under N levels and tillage methods is depicted in Fig.12 (a). A perusal of the figure indicates that the RLWC was influenced by N levels and tillage methods. It ranged from 68.2 to 74.6 per cent at the lowest and 74.8 to 80.6 per cent at the highest values of soil water potential with increase in N from 40 to 120 kg ha^{-1} respectively. At corresponding values of soil water potential, RLWC under tillage methods ranged from 69.8(T_1) to 73.5 per cent (T_2) and 78.6 (T_1) to 81.0 per cent (T_2). The tillage methods, T_1 and T_2, maintained higher RLWC (69.8 and 73.5%) than N_{40} (68.2%) and N_{80} (69.1%) levels of N, but lower than N_{120} (74.6%) at the lowest value of soil water potential.

The relationship between soil water potential and RLWC (Table 14) was linear, positive and found significant for N_{40}, N_{80} and T_1 with coefficients of correlation of $r=0.72$, 0.76 and 0.58, respectively.

4.7.2.2 Soil Water Potential and Xylem Water Potential: The relationship between soil water potential and XWP under different levels of N and tillage methods at flowering stage of wheat growth is shown in Fig.12(b). An examination of the figure reveals that XWP was influenced by N levels and tillage methods. It ranged from -20.1 (N_{40}) to -19.3 bar (N_{120}) at the lowest value of soil water potential and -17.8 (N_{40}) to -15.6 bar (N_{120}) at the highest value of soil water potential under N

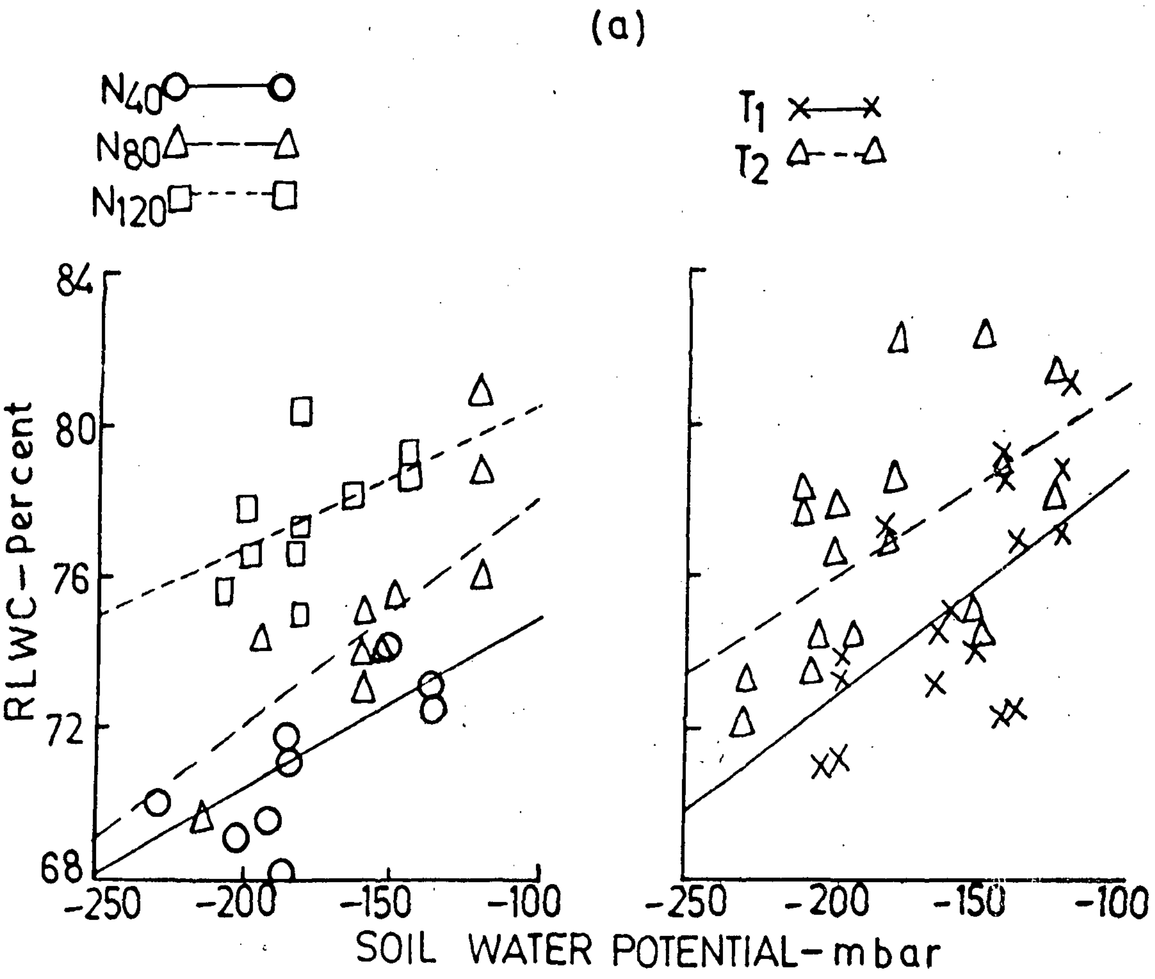
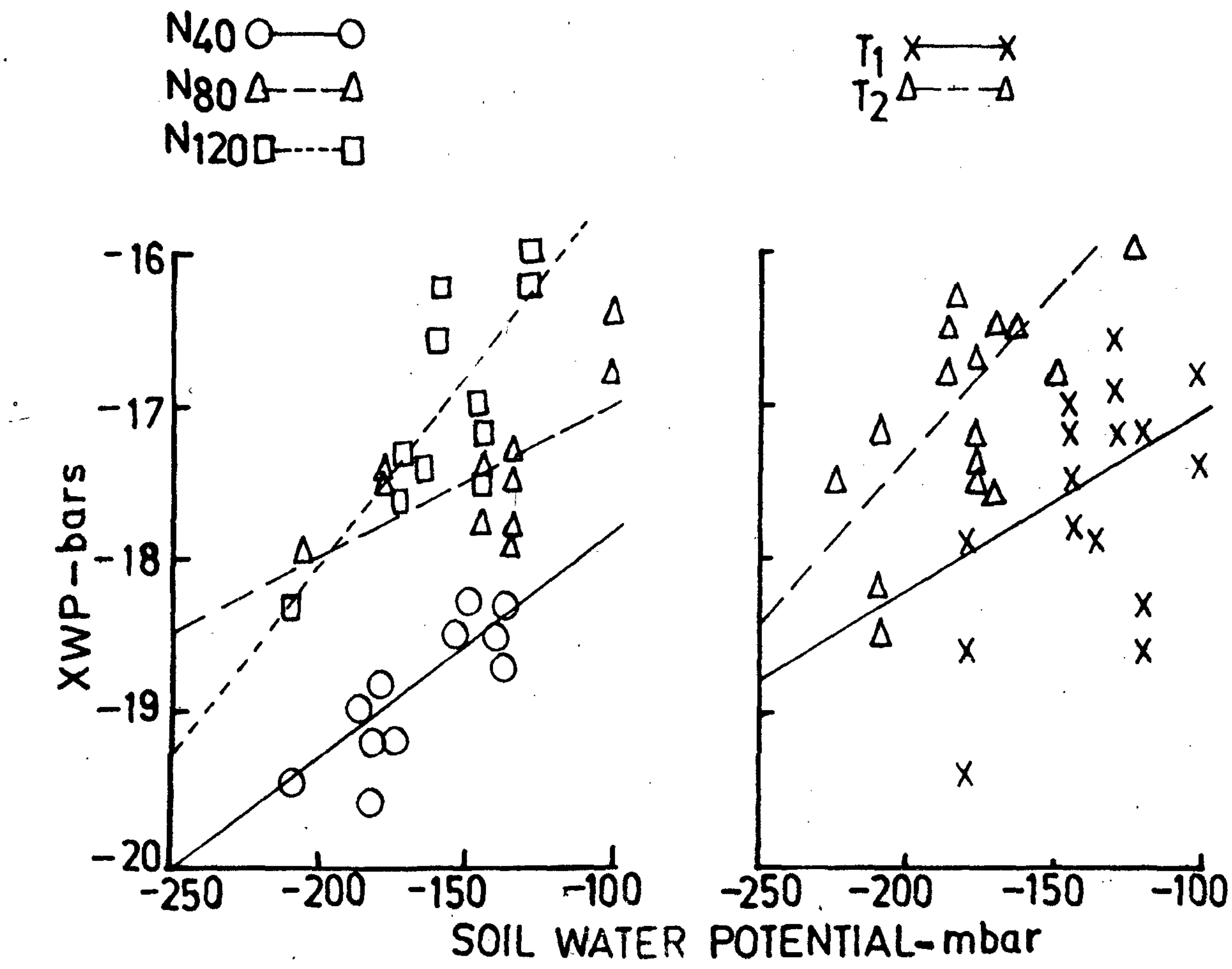


Fig.12 Relationship between soil water potential (SWP) and

(a) relative leaf water content (RLWC)
(b) xylem water potential (XWP) and
(c) leaf diffusion resistance (LDR) at flowering stage of wheat growth

(b)

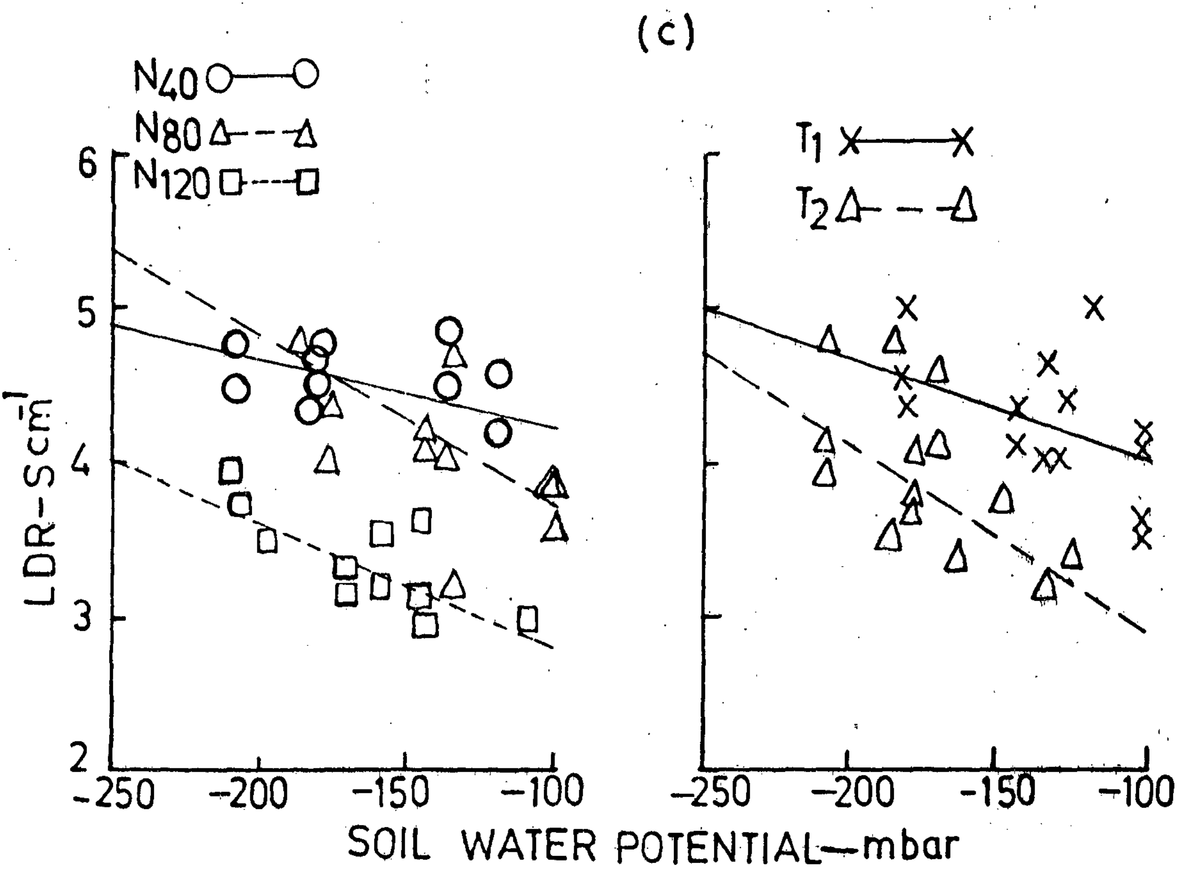


N40 ○——○
N80 △----△
N120 □-----□
T1 ×——×
T2 △----△
XWP – bars
-16
-17
-18
-19
-20
-250
-200
-150
-100
SOIL WATER POTENTIAL – mbar

levels. Under tillage methods, at corresponding soil water potentials, the XWP ranged from -13.8 (T_1) to -18.4 bar (T_2) and -17.0 (T_2) to -15.1 bar (T_2). In general, the XWP increased with increase in N levels. For example, at soil water potential of -150 mbar, the XWP was -18.6, -17.5 and -16.8 bar at N_{40}, N_{80} and N_{120}, respectively. Similarly, under tillage methods, T_1 and T_2, the XWP was -17.6 and -16.2 bar, respectively at -150 mbar soil water potential.

The relationship of soil water potential with XWP was linear, positive and found significant at N_{40}, T_{80}, N_{120} and T_2 with 'r' values of 0.85, 0.65, 0.77 and 0.64, respectively.

4.7.2.3 Soil Water Potential and Leaf Diffusion Resistance: The relationship between soil water potential and LDR under different levels of N and tillage methods at flowering stage of wheat growth is shown in Fig.12 (c). A glance at the figure indicates that LDR was influenced by N and tillage methods. Leaf diffusion resistance under N levels ranged from 4.89 (N_{40}) to 3.99 s cm^{-1} (N_{120}) and 4.21 (N_{40}) to 2.79 s cm^{-1} (N_{120}) at the lowest and the highest values of soil water potential, respectively. Similarly, under tillage methods LDR at corresponding values of soil water potential ranged from 4.89 (T_1) to 4.70 s cm^{-1} (T_2) and 3.99 (T_1) to 2.90 s cm^{-1} (T_2). In general, LDR decreased with an increase in N levels, for example, at soil water potential of -150 mbar, the LDR was 4.46, 4.09 and 3.19 s cm^{-1} at 40, 80 and 120 kg N ha^{-1}, respectively. Similarly, under tillage methods, T_1 and T_2, the LDR was 4.29

(c)
N40
N80
N120
T1
T2
LDR-Scm^{-1}
6
5
4
3
2
-250
-200
-150
-100
SOIL WATER POTENTIAL—mbar

and 3.50 s cm^{-1}, respectively at soil water potential of -150 mbar. The relationship under tillage methods was more discernible.

The relationship between soil water potential and LDR (Table 14) was linear, negative and found significant for N_{120} and T_2 with 'r' values of 0.62 and 0.55, respectively.

4.7.3 Relationships Between Water Production Functions

4.7.3.1 Xylem Water Potential and Relative Leaf Water Content: The relationship between XWP and RLWC at flowering stage of wheat growth under N levels and tillage methods is presented in Fig.13(a). An examination of the figure reveals that RLWC under N levels ranged from 69.6 (N_{40}) to 75.2 per cent (N_{120}) and 74.0 (N_{40}) to 79.9 per cent (N_{120}), at the lowest and the highest values of XWP, respectively. At corresponding values of XWP, the RLWC under tillage methods ranged from 70.6 (T_1) to 71.3 per cent (T_2) and 75.7 (T_1) to 78.2 per cent (T_2). In general, the RLWC increased with increase in N levels, for example, at XWP of -18 bar, the RLWC was 71.7, 73.7 and 76.9 per cent at 40, 80 and 120 kg N ha^{-1}, respectively. Similarly, under tillage methods, T_1 and T_2, RLWC at -18 bar XWP was 72.6 and 74.1 per cent, respectively.

The relationship of RLWC with XWP (Table 15) was linear, positive and found significant at N_{80}, N_{120}, T_1 and T_2 with correlation coefficients of r=0.84, 0.60, 0.60 and 0.77, respectively.

(a)

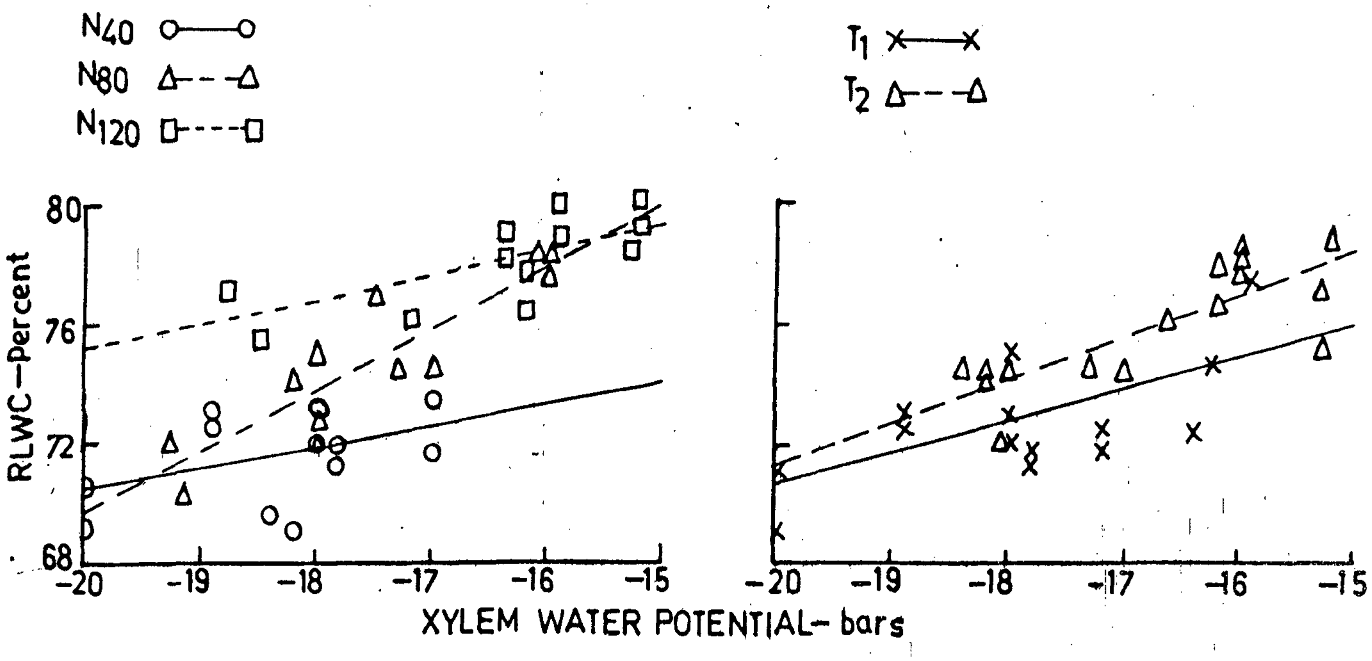


Fig.13 Relationship between water production functions

(a) xylem water potential (XWP) and relative leaf water content (RLWC)
(b) leaf diffusion resistance (LDR) and relative leaf water content (RLWC), and
(c) xylem water potential (XWP) and leaf diffusion resistance (LDR) at flowering stage of wheat growth

Table 15: Correlation coefficients 'r' for inter-relationships between plant water relations and (a) xylem water potential (XWP) and relative leaf water content (RLWC), (b) leaf diffusion resistance (LDR) and relative leaf water content (RLWC) and (c) xylem water potential (XWP) and leaf diffusion resistance (LDR) at flowering stage of wheat growth

		'r'	Number of observations
(a) Between xylem water potential (XWP) and relative leaf water content (RLWC)			
N_{40}	RLWC = 85.24 + 0.75 XWP	0.55*	12
N_{80}	RLWC = 110.96 + 2.07 XWP	0.84*	12
N_{120}	RLWC = 91.80 + 0.83 XWP	0.60*	12
T_1	RLWC = 90.80 + 1.01 XWP	0.60*	15
T_2	RLWC = 93.71 + 1.37 XWP	0.77*	15
(b) Between leaf diffusion resistance (LDR) and relative leaf water content (RLWC)			
N_{40}	RLWC = 73.22 - 1.39 LDR	-0.46	12
N_{80}	RLWC = 89.09 - 3.31 LDR	-0.82*	12
N_{120}	RLWC = 82.90 - 1.22 LDR	-0.63*	12
T_1	RLWC = 82.53 - 2.13 LDR	-0.55*	15
T_2	RLWC = 83.89 - 2.01 LDR	-0.79*	15
(c) Between xylem water potential (XWP) and leaf diffusion resistance (LDR)			
N_{40}	LDR = -3.47 - 0.45 XWP	-0.71*	12
N_{80}	LDR = -3.72 - 0.44 XWP	-0.80*	12
N_{120}	LDR = -9.31 - 0.76 XWP	-0.87*	12
T_1	LDR = -5.20 - 0.53 XWP	-0.89*	15
T_2	LDR = -5.49 - 0.53 XWP	-0.94*	15

*Significant at 5 per cent level

4.7.3.2 Leaf Diffusion Resistance and Relative Leaf Water Content:

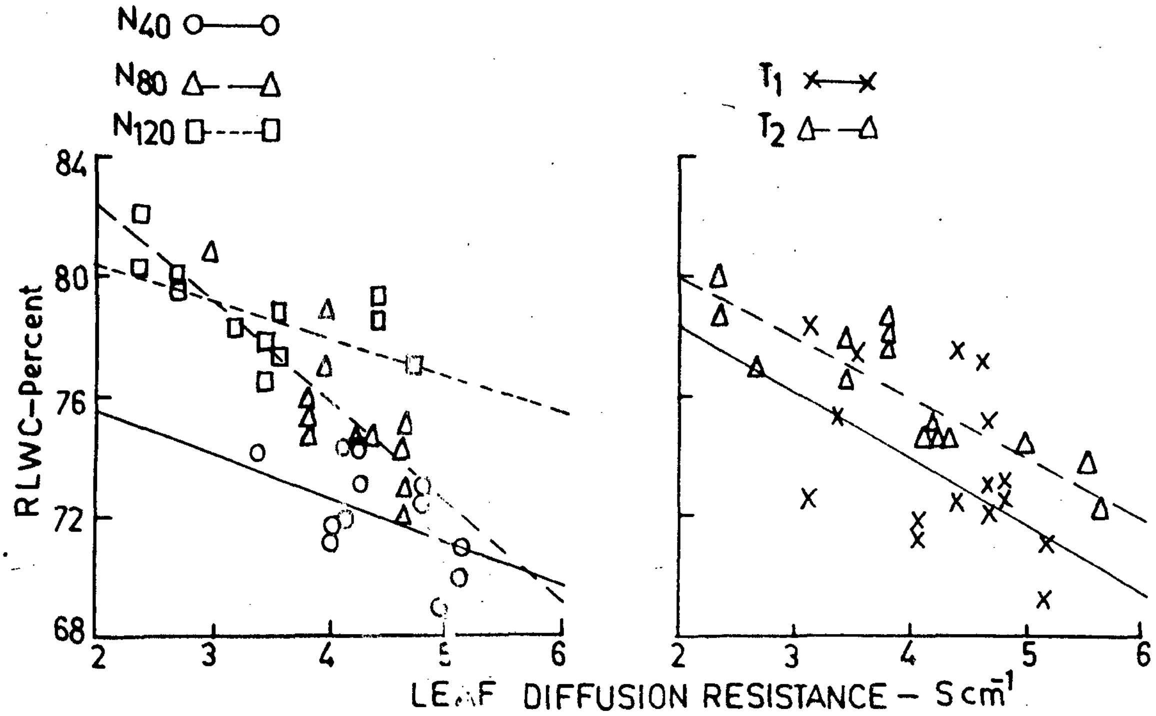
The relationship between LDR and RLWC under N levels and tillage methods at flowering stage of wheat growth is shown in Fig.13(b). An examination of the figure indicates that under N levels RLWC ranged from 75.4 (N_{40}) to 82.5 per cent (N_{120}) and 69.9 (N_{40}) to 75.6 per cent (N_{120}) at the lowest and the highest values of LDR, respectively. The changes under tillage methods at corresponding values of LDR were from 78.3 (T_1) to 79.6 per cent (T_2) and 69.8 (T_1) to 71.8 per cent (T_2). In general, the RLWC decreased with an increase in LDR. For example, at LDR of 4 s cm^{-1}, the RLWC was 72.7, 75.9 and 78.0 per cent at 40, 80 and 120 kg N ha^{-1}, respectively which decreased to 71.3, 72.5 and 76.8 per cent as LDR increased to 5 s cm^{-1}. Similarly, under tillage methods, the values were 74.0 (T_1) and 75.8 per cent (T_2) at LDR of 4 s cm^{-1}, which decreased to 71.9 (T_1) and 73.8 per cent (T_2) as LDR increased to 5 s cm^{-1}.

The relationship between RLWC and LDR (Table 15) was linear, negative and found significant for N_{80}, N_{120}, T_1 and T_2 with 'r' values of 0.82, 0.63, 0.55 and 0.79, respectively.

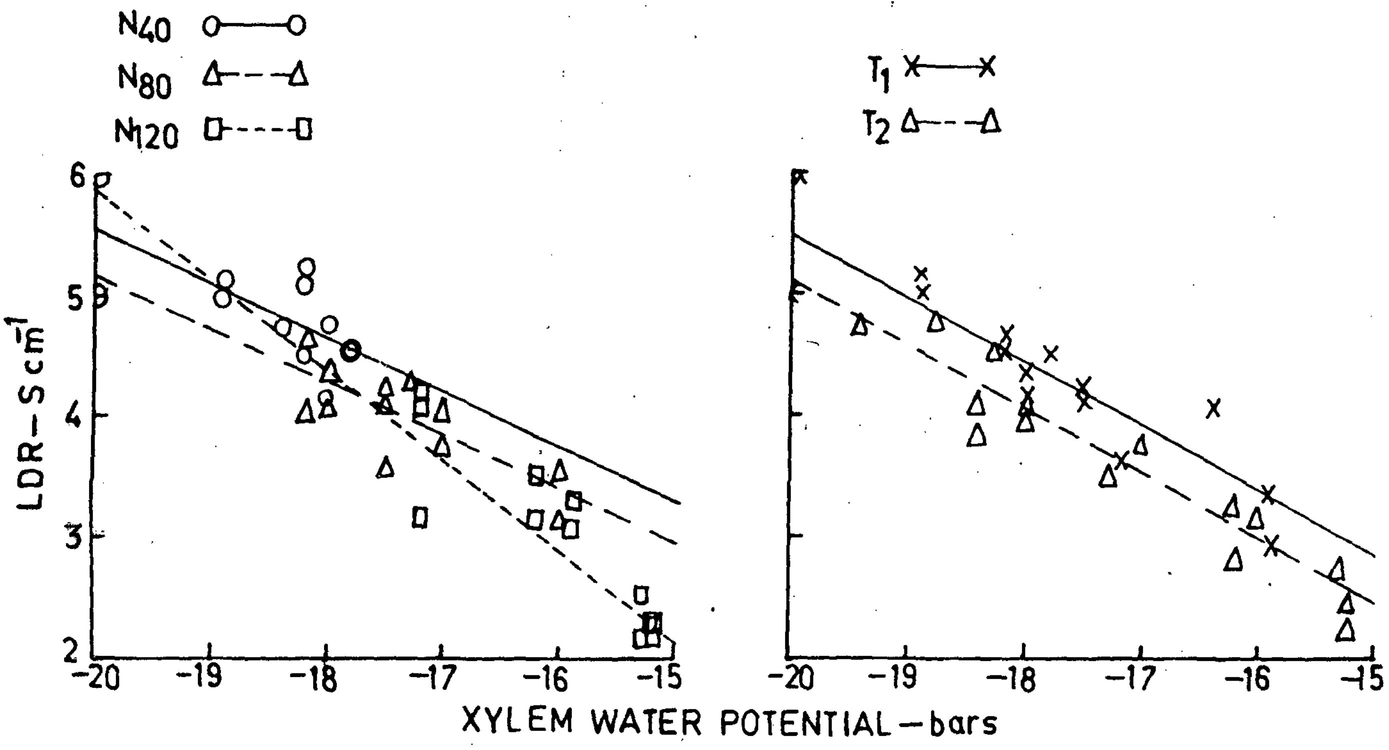
4.7.3.3 Xylem Water Potential and Leaf Diffusion Resistance:

The relationship between XWP and LDR under N levels and tillage methods at flowering stage of wheat growth is depicted in Fig.13(c). A glance at the figure reveals that under N levels, the LDR ranged from 5.53 (N_{40}) to 5.89 s cm^{-1} (N_{120}) and 3.28 (N_{40}) to 2.09 s cm^{-1} (N_{120}) at the lowest and the highest

(b)


N40
N80
N120
T1
T2
84
80
76
72
68
RLWC-Percent
2
3
4
5
6
LEAF DIFFUSION RESISTANCE – S cm-1

(c)



N40
N80
N120
T1
T2
LDR-S cm^{-1}
6
5
4
3
2
-20
-19
-18
-17
-16
-15
XYLEM WATER POTENTIAL-bars

values of XWP, respectively. At corresponding values of XWP, the LDR under tillage methods ranged from 5.40 (T_1) to 5.11 s cm^{-1} (T_2) and 2.75 (T_1) to 2.46 s cm^{-1} (T_2). In general, LDR decreased with an increase in N. For example, at XWP of -17 bar, the LDR was 4.13, 3.76 and 3.60 s cm^{-1} at 40, 80 and 120 kg N ha^{-1}, respectively. Similarly, under tillage methods, T_1 and T_2, the values were 3.81 and 3.52 s cm^{-1}, respectively at XWP of -17 bar.

The relationship between XWP and LDR (Table 15) was linear, negative and found significant at all levels of N having 'r' values of 0.71, 0.80, and 0.87 at 40, 80 and 120 kg N ha^{-1}, respectively. For tillage methods, T_1 and T_2, the 'r' values were 0.89 and 0.94, respectively.

4.8 Plant Growth Studies

4.8.1 Leaf Area Index

Leaf Area index (LAI) studies at maximum tillering and flowering stages of wheat growth during the years 1989-90 and 1990-91 is presented in Table 16a. A perusal of the data reveals that there was significant increase in LAI with N levels at both the stages during both the years of study. Leaf area index increased from 1.63 at N_{40} to 2.08 at N_{120} at maximum tillering and 2.56 at N_{40} to 3.28 at N_{120} at flowering. Similar results were obtained during the second year of study and the corresponding changes at the two stages in LAI with

Table 16a: Effect of nitrogen levels, tillage methods and water stocks on leaf area index at different stages of wheat growth

Treatments	1989-90		1990-91	
	Stages of wheat growth			
	MT	FS	MT	FS
Nitrogen levels (N)				
N_{40}	1.63	2.56	1.48	2.40
N_{80}	1.87	2.91	1.60	3.08
N_{120}	2.08	3.28	1.95	3.39
CD 0.05	0.19	0.32	0.25	0.25
Tillage methods (T)				
T_1	1.69	2.73	1.51	2.88
T_2	2.03	3.00	1.64	3.04
CD 0.05	0.16	0.26	NS	NS
Water stocks (W)				
W_1	1.74 (35.0)	2.77 (31.2)		
W_2	1.84 (36.4)	2.98 (30.8)		
W_3	1.99 (37.3)	2.95 (31.1)		
CD 0.05	NS	NS		

MT = Maximum tillering, FS = Flowering stage

Figures in parentheses are water stocks (cm)

increase in N from 40 to 120 kg ha^{-1} were 1.18 to 1.95 and 2.40 to 3.39.

The tillage methods increased LAI significantly (Table 16a) during the year 1989-90 from 1.69 (T_1) to 2.03 (T_2) at maximum tillering and 2.73 (T_1) to 3.10 (T_2) at flowering. During the second year of study the effect was not significant, but the trend was same to that of first year of study, i.e. LAI increased from 1.51 (T_1) to 1.64 (T_2) and 2.88 (T_1) to 3.04 (T_2) at maximum tillering and flowering stages, respectively.

Since variable water stocks could not be achieved in the field, hence there was no effect of water stocks on LAI (Table 16a) at any growth stage (1989-90). During the second year of study, these observations were not recorded.

The interaction NxT was found significant at maximum tillering stage during the year 1989-90 (Table 16b).

Table 16b: Interaction effect of nitrogen levels and tillage methods on leaf area index at maximum tillering stage of wheat growth

Tillage methods		Nitrogen levels	
	N_{40}	N_{80}	N_{120}
T_1	1.56	1.75	1.98
T_2	1.70	1.98	2.17
CD 0.05	0.25		

A perusal of the data reveals that under T_1, LAI increased from 1.56 at N_{40} to 1.98 at N_{120}, but the increase was not significant. Similarly, under T_2, LAI increased with increase in N level, but the significant increase was from 1.70 at N_{80} and 1.98 at N_{120}. The treatment N_{120} T_2 was found significantly superior over the treatments of N_{40} T_1, $N_{40}T_2$ and $N_{80}T_1$.

At maximum tillering stage the LAI (Table 16a) was higher and at flowering stage it was lower during 1989-90 in comparison to the values during the year 1990-91. The level 120 kg N ha^{-1} gave 27.6 and 28.1 per cent; 65.3 and 41.3 per cent higher LAI over 40 kg N ha^{-1} at maximum tillering and flowering stages during the years 1989-90 and 1990-91, respectively. The increase in T_2 over T_1 for the two years of study was 20.1 and 9.9 per cent; 8.6 and 5.6 per cent, respectively. The LAI increased with time and the increase was 0.93, 1.04 and 1.20 at N_{40}, N_{80} and N_{120}, respectively during the year 1989-90 from maximum tillering to flowering. The corresponding increase, for the second year was 1.22, 1.48 and 1.44. Similarly, under tillage methods, T_1 and T_2, the increase was 1.04 and 0.97; 1.37 and 1.40 from maximum tillering to flowering during the years 1989-90 and 1990-91, respectively. The increase with age was more during the year 1990-91 than the year 1989-90 both under N levels and tillage methods.

4.8.2 Dry Matter Production

The dry matter production recorded at important growth stages, viz., crown root initiation, maximum tillering, flowering and at crop harvest (grain and straw yield) during the years 1989-90 and 1990-91 is presented in Table 17. An examination of the data reveals that there was significant effect of N on dry matter production at all the growth stages during both the years of study. The dry matter production increased significantly with N levels from 25.4 and 89.4 g m^{-2} at 40 kg N ha^{-1} to 43.3 and 163.5 g m^{-2} at 120 kg N ha^{-1} at crown root initiation and maximum tillering stages, respectively during the year 1989-90. At third stage, i.e. flowering, the significant increase was from 313.9 g m^{-2} at N_{40} to 398.2 g m^{-2} at N_{80}. The dry matter production further increased to 435.2 g m^{-2} at N_{120}, but the increase was not significant. During the second year of study, the dry matter production significantly increased from 28.3 (N_{40}) to 54.7 g m^{-2} (N_{120}) and 115.6 (N_{40}) to 161.5 g m^{-2} (N_{120}) at crown root initiation and maximum tillering stages, respectively. This increase was not significant at both these stages with increase in N from 80 to 120 kg ha^{-1}. At third stage, i.e. flowering, the dry matter production increased significantly from 332.40 to 473.8 g m^{-2} with increase in N level from 40 to 120 kg ha^{-1}.

The tillage methods increased dry matter production (Table 17) from 32.2, 117.2 and 355.7 g m^{-2} (T_1) to 35.7, 136.4 and 409.2 g m^{-2} (T_2) at crown root initiation, maximum

Table 17: Effect of nitrogen level, tillage methods and water stocks on dry matter production at different stages and harvest of wheat crop

	1989-90					1990-91				
	Stages of wheat growth ($g\ m^{-2}$)			At harvest ($q\ ha^{-1}$)		Stages of wheat growth ($g\ m^{-2}$)			At harvest ($q\ ha^{-1}$)	
	CRI	MT	FS	Grain	Straw	CRI	MT	FS	Grain	Straw
Nitrogen levels (N)										
N_{40}	25.4	89.4	313.9	20.4	46.4	28.3	116.6	332.4	23.6	48.3
N_{80}	34.7	127.4	398.2	25.2	35.7	35.7	145.2	430.9	31.9	60.8
N_{120}	43.3	163.5	435.2	29.0	62.9	54.7	161.5	473.8	32.9	65.8
CD 0.05	5.9	10.8	55.3	2.4	6.1	9.4	22.5	38.8	4.6	7.1
Tillage methods (T)										
T_1	32.2	117.2	355.7	23.3	53.5	37.0	130.3	388.7	27.6	57.1
T_2	35.7	136.4	409.2	26.7	56.3	43.3	151.9	436.0	31.4	59.5
CD 0.05	NS	8.9	45.1	2.0	NS	NS	18.3	31.7	3.8	NS
Water stocks (W)										
W_1		120.5 (35.0)	356.7 (31.2)	24.8 (30.7)	54.8				27.6 (29.5)	55.4
W_2		124.1 (36.4)	413.4 (30.8)	25.5 (30.1)	55.5				30.7 (30.5)	59.9
W_3		135.8 (37.3)	377.2 (31.1)	24.6 (31.0)	55.3				30.0 (29.7)	59.4
CD 0.05		NS	NS	NS	NS				NS	NS

CRI = Crown root initiation, MT = Maximum tillering, FS = Flowering stage

Figures in parentheses are water stocks (cm)

tillering and flowering stages, respectively during the year 1989-90. But the significant increase was at maximum tillering and flowering stages only. Similar results were obtained during the year 1990-91 and the corresponding values of dry matter were 37.0, 130.3 and 388.7 g m^{-2} at T_1, and 43.3, 151.9 and 436.0 g m^{-2} at T_2.

There was no significant effect of water stocks on dry matter production (Table 17) at maximum tillering and flowering stages, during the year 1989-90. During the year 1990-91, these observations were not recorded.

In general (Table 17), it was observed that the dry matter production at different growth stages during the year 1990-91 was higher than the year 1989-90. The level 120 kg N ha^{-1} showed 70.5, 82.9 and 38.6 per cent higher dry matter over 40 kg N ha^{-1} at crown root initiation, maximum tillering and flowering stages, respectively during the first year of crop study. The corresponding per cent increases during the second year of study were 93.3, 39.7 and 42.5. Similarly, under the tillage methods, T_2 produced 10.9, 16.4 and 15.0 per cent higher dry matter over T_1 at crown root initiation, maximum tillering and flowering stages, respectively, during the year 1989-90. The corresponding increases during the second year were 17.0, 16.6 and 12.2 per cent. Water stocks, W_3 and W_2 gave 12.7 and 15.8 per cent higher dry matter over W_1 at maximum tillering and flowering stages, respectively.

4.8.3 Grain and Straw Yield

The effect of N levels, tillage methods and water stocks on crop yield (grain and straw) during the years 1989-90 and 1990-91 is presented in Table 17. The grain and straw yield during the year 1989-90 increased significantly from 20.4 and 46.4 q ha^{-1} to 29.0 and 62.9 q ha^{-1}, respectively with increase in N from 40 to 120 kg N ha^{-1}. During the second year of study, the grain and straw yield increased from 23.6 and 48.3 q ha^{-1} at N_{40} to 32.9 and 65.8 q ha^{-1} at N_{120}, respectively. But the significant increase was with an increase in N from 40 to 80 kg ha^{-1} (31.9 and 60.8 q ha^{-1}).

The tillage methods increased the grain and straw yield (Table 17) from 23.3 and 53.5 q ha^{-1} (T_1) to 26.7 and 56.3 q ha^{-1} (T_2), respectively during the year 1989-90. Similarly, like the previous year, the grain and straw yield increased from 27.6 and 57.1 q ha^{-1} at T_1 to 31.4 and 59.5 q ha^{-1} at T_2 during the year 1990-91. The significant increase under tillage methods was only for grain yield during both the years of study.

The water stocks did not reflect their effect on grain and straw yield during both the years of study (Table 17).

In general (Table 17), it was observed that N_{120} gave 42.2 and 35.5 per cent higher grain and straw yield, respectively over N_{40} during the first year of study. The corresponding values for the second year were 39.4 and 36.2

per cent. Similarly, under tillage methods, T_2 showed 14.6 and 5.2 per cent higher grain and straw yield, respectively over T_1 during the year 1989-90 and 13.8 and 4.2 per cent higher during the year 1990-91. The per cent increase in grain and straw yield under N levels was more than the tillage methods. But it was almost of same magnitude during the two years of study.

4.8.4 Nitrogen Content in Plant

The N content determined at crown root initiation, maximum tillering, flowering and at crop harvest in grain and straw is presented in Table 13. A perusal of the data reveals that there was significant effect of N on its content in plant at different growth stages and at crop harvest in grain and straw during both the years of study. At crown root initiation and at crop harvest in grain, the N content increased from 0.62 and 2.25 per cent at N_{40} to 0.72 and 2.46 per cent at N_{120}, respectively. The significant increase with increase in N level was from 0.66 and 2.32 per cent (80 kg N ha^{-1}) to 0.72 and 2.46 per cent (120 kg N ha^{-1}) during the first year of crop study. At maximum tillering, flowering and at crop harvest in straw, N content increased significantly from 0.97, 1.40 and 0.22 per cent to 1.18, 1.80 and 0.37 per cent, respectively with increase in N from 40 to 120 kg ha^{-1}. During the second year of crop study, N content increased from 0.53, 0.95 and 0.22 per cent at N_{40} to 0.72, 1.15 and 0.39 per cent at N_{120} at crown root initiation, maximum tillering and at crop harvest in

Table 18: Effect of nitrogen levels, tillage methods and water stocks on nitrogen content(%), in plant at different stages and harvest of wheat crop

Treatments	1989-90					1990-91				
	Stages of wheat growth			At harvest		Stages of wheat growth			At harvest	
	CRI	MT	FS	Grain	Straw	CRI	MT	FS	Grain	Straw
Nitrogen levels (N)										
N_{40}	0.62	0.97	1.40	2.25	0.22	0.58	0.95	1.34	2.12	0.22
N_{80}	0.66	1.08	1.62	2.32	0.31	0.68	0.99	1.46	2.27	0.26
N_{120}	0.72	1.18	1.80	2.46	0.37	0.72	1.15	1.68	2.43	0.39
CD 0.05	0.07	0.08	0.08	0.12	0.04	0.07	0.13	0.22	0.20	0.06
Tillage methods (T)										
T_1	0.65	1.07	1.64	2.33	0.29	0.64	1.05	1.42	2.15	0.28
T_2	0.68	1.09	1.65	2.38	0.31	0.68	1.06	1.56	2.35	0.32
CD 0.05	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Water stocks (W)										
W_1		1.12 (35.0)	1.65 (31.2)	2.33 (30.7)	0.33				2.31 (29.5)	0.31
W_2		1.06 (36.4)	1.67 (30.8)	2.33 (30.1)	0.30				2.32 (30.5)	0.30
W_3		1.06 (37.3)	1.61 (31.1)	2.46 (31.0)	0.29				2.20 (29.7)	0.29
CD 0.05		NS	NS	NS	NS				NS	NS

CRI = Crown root initiation, MT = Maximum tillering, FS = Flowering stage

Figures in parentheses are water stocks (cm)

straw, respectively. At crown root initiation the significant increase with N levels was from 0.58 (N_{40}) to 0.68 per cent (N_{80}). At maximum tillering and at crop harvest in straw, the significant increase in N content was from 0.99 and 0.26 per cent at N_{80} to its content at N_{120}. At flowering and at crop harvest in grain the level 120 kg N ha^{-1} showed significantly higher N content, the values being 1.68 and 2.43 per cent over 40 kg N ha^{-1} of 1.34 and 2.12 per cent, respectively. But the increase with N level was not significant. At flowering, the levels 80 kg N ha^{-1} (1.46%) and 120 kg N ha^{-1} (1.68%) were at par with each other.

Under tillage methods, N content (Table 18) increased from 0.65, 1.07, 1.64, 2.33 and 0.29 per cent at T_1 to 0.68, 1.09, 1.65, 2.38 and 0.31 per cent at T_2, at crown root initiation, maximum tillering, flowering and at crop harvest in grain and straw, respectively during the first year of crop study. Nitrogen content at the corresponding stages during the second year of study increased from 0.64, 1.05, 1.42, 2.15 and 0.28 per cent at T_1 to 0.68, 1.06, 1.56, 2.35 and 0.32 per cent at T_2. There was no significant effect of tillage methods on N content in plant at any growth stage during both the years of crop study.

There was no significant effect of water stocks on N content in plant at any growth stage and at crop harvest in grain and straw during both the years of study (Table 18).

4.8.5 Nitrogen Uptake

Nitrogen uptake at different stages of wheat growth and at crop harvest in grain and straw during the years 1989-90 and 1990-91 is presented in Table 19. A perusal of the data indicates that there was significant effect of N on its uptake at different stages during both the years of crop study. Nitrogen uptake increased significantly from 0.16, 0.87 and 4.42 g m^{-2} to 0.32, 1.92 and 7.88 g m^{-2} at crown root initiation, maximum tillering and flowering stages, respectively, with an increase in N level from 40 to 120 kg ha^{-1} during the first year of study. Similar results were obtained during the second year of crop study and N uptake increased significantly from 0.17, 1.10 and 4.60 g m^{-2} to 0.38, 1.87 and 7.86 g m^{-2} at crown root initiation, maximum tillering and flowering stages, respectively.

Under tillage methods, N uptake (Table 19) increased from 0.23, 1.28 and 5.83 g m^{-2} (T_1) to 0.25, 1.49 and 6.72 g m^{-2} (T_2) at crown root initiation, maximum tillering and flowering stages, respectively, during the year 1989-90. This increase, except at crown root initiation, was significant at both the growth stages. Similar results were obtained during the second year of study and N uptake increased from 0.23, 1.31 and 5.61 g m^{-2} (T_1) to 0.30, 1.63 and 6.89 g m^{-2} (T_2) at crown root initiation, maximum tillering and flowering stages of wheat growth, respectively.

Table 19: Effect of nitrogen levels, tillage methods and water stocks on nitrogen uptake at different stages and harvest of wheat crop

Treatments	1989-90					1990-91				
	Stages of wheat growth (g m^{-2})			At harvest (kg ha^{-1})		Stages of wheat growth (g m^{-2})			At harvest (kg ha^{-1})	
	CRI	MT	FS	Grain	Straw	CRI	MT	FS	Grain	Straw
Nitrogen levels (N)										
N_{40}	0.16	0.87	4.42	45.89	10.12	0.17	1.10	4.60	50.16	10.96
N_{80}	0.23	1.37	6.45	59.46	17.00	0.26	1.45	6.29	72.11	15.65
N_{120}	0.32	1.92	7.88	71.06	23.27	0.38	1.87	7.86	80.16	26.00
CD 0.05	0.04	0.16	0.73	4.37	1.80	0.07	0.14	1.20	6.32	4.68
Tillage methods (T)										
T_1	0.23	1.28	5.83	54.07	15.27	0.23	1.31	5.61	59.20	16.13
T_2	0.25	1.49	6.72	63.55	17.78	0.30	1.63	6.89	75.76	18.92
CD 0.05	NS	0.13	0.60	3.98	1.47	NS	0.25	0.98	11.50	NS
Water stocks (W)										
W_1		1.37 (35.0)	5.89 (31.2)	57.84 (30.7)	17.96				64.04 (29.5)	17.04
W_2		1.33 (36.4)	6.90 (30.8)	59.58 (30.1)	16.90				71.58 (30.5)	17.99
W_3		1.45 (37.3)	6.08 (31.1)	59.09 (31.0)	15.82				66.9 (29.7)	17.55
CD 0.05		NS	NS	NS	NS				NS	NS

CRI = Crown root initiation, MT = Maximum tillering, FS = Flowering stage

Figures in parentheses are water stocks (cm)

There was no significant effect of water stocks on N uptake (Table 19) at maximum tillering and flowering stages during the year 1989-90. During the year 1990-91, these observations were not recorded.

Nitrogen uptake in grain and straw increased significantly (Table 19) from 45.89 and 10.12 kg ha^{-1} to 71.06 and 23.27 kg ha^{-1}, respectively, with an increase in N level from 40 to 120 kg ha^{-1} during the year 1989-90. Similar results were obtained during the year 1990-91, and N uptake in grain and straw increased significantly from 50.16 and 10.96 kg ha^{-1} at N_{40} to 80.16 and 26.00 kg ha^{-1} at N_{120}, respectively.

Under tillage methods, N uptake in grain and straw (Table 19) increased significantly from 54.07 and 15.67 kg ha^{-1} (T_1) to 63.55 and 17.78 kg ha^{-1} (T_2), respectively, during the year 1989-90. During the second year of study, N uptake in grain increased significantly from 59.20 (T_1) to 75.76 kg ha^{-1} (T_2). In straw, it increased from 16.13 (T_1) to 18.92 kg ha^{-1} (T_2), but the increase was not significant.

Since variable water stocks could not be achieved in the field hence there was no effect of water stocks on N uptake (Table 19) at crop harvest in grain and straw during both the years of crop study.

DISCUSSION

DISCUSSION

Present studies were conducted at the experimental farm of Himachal Pradesh Krishi Vishvavidyalaya, Palampur (Kangra) for two years during the period from November to May in 1989-90 and 1990-91. Wheat(VL-421) was used as a test crop. The treatments included three levels of N viz., 40 (N_{40}), 80 (N_{80}) and 120 (N_{120}) kg ha^{-1}, two tillage methods viz., conventional tillage (T_1) and deep ploughing (T_2), and three water stocks viz., W_1, W_2 and W_3 in the soil profile. The studies aimed at evaluating the effect of these treatments on water extraction pattern, plant water stress and plant growth. The water stress at different growth stages has been expressed in terms of different water production functions like relative leaf water content (RLWC), xylem water potential (XWP), leaf diffusion resistance (LDR) and stress degree days (SDD). The different plant water indices have been correlated with soil water status.

Mechanical composition of the soil of experimental site indicated that the soil texture is silty clay loam (Table 2). Clay content is higher (32.9%) in 30-45 cm and lowest (28.8%) in 60-75 cm layer. The silt content decreases with depth from 49.6 per cent for 0-15 cm to 30.8 per cent for 75-90 cm depth. But the sand content increases with depth from 20.6 per cent for 0-15 cm to 30.8 per cent for 75-90 cm depth. The bulk density of the profile increased with depth from 1.10 Mg m^{-3} for 0-15 cm to 1.36 Mg m^{-3} for 75-90 cm depth (Table 2). In

0-15 and 15-30 cm depths the bulk density at the time of imposition of tillage treatments under deep ploughing (T_2) was lower than that under conventional tillage (T_1) during both the years of study (Table 2). This was due to more loosening of soil under T_2. As is apparent from Table 2, the mean weight diameter (MWD) in general is higher, the value is minimum (1.82 mm) for 15-30 cm and maximum (2.46 mm) for 30-45 cm depth. The soil dominates in oxides of Fe, Al and Mn (Bishnoi et al, 1987) and may be ascribed as one of the reasons for higher values of MWD. The water retention at or around field capacity in the surface 0-15 and 15-30 cm depths is poor in comparison to subsurface depths (Fig.1, Table 2). This may be due to higher values of MWD and lower bulk density in surface layers. The depth of 75-90 cm retained maximum and 0-15 cm the minimum amount of water at all values of matric suction.

Available water capacity (AWC) worked out to be 16 and 10 per cent, 15 and 10 per cent, 16.7 and 13.7 per cent, 13 and 10 per cent, 16 and 11 per cent and 16.3 and 10.8 per cent by volume at limits of 1/10 to 15 and 1/3 to 15 bar for the layers 0-15, 15-30, 30-45, 45-60, 60-75 and 75-90 cm, respectively. Available water capacity for 30-45 cm layer was the highest, whereas, 45-60 cm layer showed the lowest value of AWC and was comparable with other depths. For all depths, the decrease in water content from 0 to 100 mbar suction was quite rapid and became gradual beyond 100 mbar suction (Fig.1). The decrease in water content from 0 to 100 mbar suction for the surface 0-30 cm layer was as high as 17.0 per cent by volume. The saturated hydraulic conductivity (K_s) decreased with depth as the bulk density increased (Table 3). For 15-30 and 30-45 cm layers, having higher clay content and bulk density than the surface layer, the saturated hydraulic conductivity (K_s) was lower than the surface 0-15 cm layer.

The in situ hydraulic conductivity '$K(\theta)$', determined during the internal drainage of the profile at the experimental site (Fig.3), was identical for 0-15-30-45 cm and 45-60-75-90cm layers. Hence, for the purpose of computing fluxes within the root zone, a combined '$K(\theta)$' relation was derived separately, one for 0-15-30-45 cm layers and the other for 45-60-75-90 cm layers. In the '$K(\theta)$' relationship the exponent 'b' related to the permeability function, was slightly lower for 0-15-30-45 cm layers in comparison to the subsurface layers of 45-60-75-90 cm. This may be ascribed to higher percentage of sand in lower layers. The values of hydraulic conductivity obtained from the field data were used to estimate the fluxes within the root zone.

The data on soil water content and matric potential for the first year of study were used to compute the root water uptake (r_z) during a typical drying period from 140 to 170 days after sowing (DAS). During the second year, the rainfall was slightly less than the first year, but was more uniformly distributed and no well defined dry period was available. During both the years of study, attempts were made at maximum tillering stage of crop growth to vary the water stocks depending upon the antecedent soil moisture. But because of high frequency of rainfall the water stocks could not exactly be modified or there was difficulty in varying the water stocks. The total rainfall received during complete growing season of wheat for the years 1989-90 and 1990-91 was 650.3 and 612 mm, respectively.

The changes in soil water content (Fig.4) and hydraulic gradients (Fig.5) showed that during the drying period between 140 to 170 days after sowing (DAS), the crop extracted water upto 30 cm depth under low fertility level ($N_{40}T_1$ and $N_{40}T_2$) and upto 45 cm depth under the remaining treatments.

The decrease in water content (Fig.4) and change in hydraulic gradient (Fig.5) were maximum upto 45 cm depth under the recommended fertility level ($N_{120}T_1$ and $N_{120}T_2$). In case of treatments $N_{40}T_1$ and $N_{40}T_2$, the gradients in 15-30 cm depth were downward upto 150 DAS, but thereafter showed steep upward increase. Similarly, the gradients in 30-45 cm depth also remained downward upto 155 DAS under $N_{40}T_1$ and $N_{40}T_2$ and later this increase was in upward direction, but of small magnitude, i.e. the values remained near the zero line of gradients. This is further substantiated by the fact that the changes in water content in 0-15 cm layer under low fertility level ($N_{40}T_1$ and $N_{40}T_2$) were also minimum. Generally, the upward increase in hydraulic gradients and decreases in water contents were higher under higher fertility level and deep ploughing ($N_{120}T_2$). This may be due to the fact that 120 kg N ha^{-1} increased the root growth (Tables 7, 8 and 9). The deep ploughing (T_2) because of beneficial effect of decrease in bulk density helped the roots to penetrate to subsurface layers and thereby increased the utilization of subsoil moisture, resulting in greater upward increase in gradients. Greater utilization of subsoil moisture with higher levels of N has also been reported by several workers (Kmoch <u>et al.</u>, 1957; Campbell <u>et al.</u>, 1977; Yadav and Agarwal, 1981). However, the depth of 60-75 cm showed upward increase of gradients after 155 DAS under the treatments of $N_{120}T_1$ and $N_{120}T_2$ but there was no change in water content under these treatments at this depth. In general, the hydraulic gradients were near the zero line below 45 cm under all the treatments. McGowan (1974) and Gregory <u>et al.</u> (1978) have defined the effective rooting depth as that depth at which the hydraulic gradients are zero. The maximum rooting depth in these studies worked out to be 30 cm under the treatments of $N_{40}T_1$, $N_{40}T_2$ and upto 45 cm under the remaining treatments. This is further substantiated by the magnitude and direction of hydraulic flux estimated at 82.5 cm depth (Fig.6). The changes in hydraulic flux under all the treatments during this drying period highlighted the extent of root activity in the rooting zone which induced the flow towards the surface. The flux remained downward under all the treatments for most of the time. It was only at the end of drying period (160 to 165 DAS) that the flux under the treatments of $N_{40}T_1$, $N_{80}T_1$ and $N_{80}T_2$ passed the line of zero flux and turned upward (Fig.6). Under the remaining treatments the flux became upward between 145 to 150 DAS as the dry period progressed.

The total water uptake (R_z) from the profile (0 to 90cm) increased with increase in N level both under conventional tillage (T_1) and deep ploughing (T_2). The comparison of different treatments (Fig.7) showed that the value of R_z was maximum (0.392 cm d^{-1}) under $N_{120}T_2$ and minimum (0.135 cm d^{-1}) under $N_{40}T_1$. The root growth in 0-30 cm layer (Tables 7, 8 and 9) was also higher at N_{120} and under T_2. Ehrler et al. (1980) found that root water uptake was functionally related to rooting density and soil water potential. Similarly, Nnyamah and Black (1977) and Chaudhary and Bhatnagar (1980) found a close correspondence between the rooting density, root distribution and water extraction pattern. Under tillage methods, the value of both r_z and R_z were higher under T_2 (Appendix III). This could be ascribed to beneficial effect of deep ploughing (T_2) on soil physical properties resulting in better root growth and higher water uptake. Burnett and Tackett (1968) and Bhadoria (1988) indicated that deep ploughing modifies the soil physically and results in greater utilization of subsoil moisture. Deeper and denser rooting resulting in higher water uptake under deep tillage has also been reported by several

Upreti and Sirohi (1986) had also recorded higher value of RLWC at higher N nutrition but the effect was not significant. They reported that the application of N regulated the plant water relations, i.e. osmotic potential decreases and XWP increases which resulted in higher RLWC. At maximum tillering and flowering stages, the deep tillage (T_2) maintained higher RLWC of 78.2 and 76.3 per cent than conventional tillage (T_1), being 76.8 and 75.5 per cent, respectively during the year 1989-90 (Table 10). But during second year of study, the RLWC values were almost same under both the tillage methods at both the stages of crop growth. The higher RLWC values under deep ploughing (T_2) might be due to improvement in soil bulk density (Table 2) which resulted in higher water availability and thereby enhanced root growth and its activity. Similar observations were also made by Burnett and Tacket (1968), Bennie and Botha (1986), Barbosa <u>et al</u>. (1989), Arora <u>et al</u>. (1991) and Gajri <u>et al</u>. (1991). The RLWC decreased as the crop advanced from maximum tillering to flowering stage. This may be ascribed to comparatively higher air temperature during flowering stage (Appendix I and II) which might have resulted in greater transpiration losses, thereby decreasing RLWC.

Plant water potential is a measure of energy status of plant water and is a good index of physiological and biochemical phenomenon taking place in plant. Plant water potential expressed as xylem water potential (XWP) is directly related to the integrated influence of soil water, plant factors and evaporative demand of the atmosphere. In the present study, XWP increased with N application at all the growth stages during both the years of study (Table 11a). The effect of N was significant at all the growth stages during 1989-90 and only at flowering stage during the year 1990-91. At crown root initiation, maximum tillering and flowering stages, the 120 kg N ha^{-1} maintained 18.9, 5.4 and 12.3 per cent higher XWP over 40 kg N ha^{-1} during the year 1989-90 and 5.9, 4.1 and 8.9 per cent during 1990-91, respectively. The increase in XWP with N application could be ascribed to increase in tissue elasticity (bulk modulus of elasticity) and apoplastic water content of leaf (Upreti and Sirohi, 1986). Nitrogen fertility influences plant water relations (Shimshi, 1970; Radin and Parker, 1979; Radin and Boyer, 1982) and N deficiency decreases leaf water potential as a result of increased root resistance (Radin and Parker, 1979). The increase in XWP could be ascribed to better root growth resulting in higher water uptake. Gajri and Prihar (1985) reported that higher root density had a large influence on leaf water potential of wheat through its effect on water uptake, at a given water potential in soil. In their field experiment, leaf water potential of wheat increased with increase in rooting density even though the root zone soil water content was lower in higher root density plots. In the present study the XWP was higher under deep ploughing (T_2) at all the growth stages during both the years of study (Table 11a). The significant effect of tillage methods, however, was only at maximum tillering and flowering stages during the year 1989-90. The tillage method T_2 maintained 1.1, 4.7 and 4.6 per cent higher XWP over T_1 during 1989-90; 2.1, 4.7 and 2.9 per cent during 1990-91 at crown root initiation, maximum tillering and flowering stages, respectively. This could probably be due to improvement in soil physical properties resulting in better root growth and higher uptake of water. Similar observations have also been made by Burnett and Tackett (1968), Reddy <u>et al.</u> (1977), Bhadoria (1988), Arora <u>et al.</u> (1991) and Gajri <u>et al.</u> (1991). Deep ploughing (T_2) has favourable effect on the modifications of soil physical properties, viz., infiltration, increase in drainage of poorly drained soil, bulk density and porosity of soil (Yumura and Ishihara, 1971; Allamaras <u>et al.</u>, 1977; Acharya and Bhagat, 1984). The treatment $N_{120}T_2$ was found significantly superior for XWP over $N_{40}T_1$ and $N_{40}T_2$ at crown root initiation during the year 1989-90 (Table 11b). This could be due to higher root growth at higher level of N and deep ploughing (T_2) which produced favourable conditions for penetration of roots to deeper depths and thus extracted greater amount of subsoil moisture. Xylem water potential decreased as the crop advanced in age, i.e. crown root initiation to flowering stage. This is due to high evaporative demand (Appendix I and II) at flowering than at crown root initiation and maximum tillering stages as the leaf water potential is highly affected by evaporative conditions such as relative humidity and net radiation as long as soil water is not limiting (Slayter and Gardner, 1965). Similar results for wheat have also been earlier reported (Anonymous, 1977; Singh _et al._, 1984).

The critical values of LWP decreases with increasing temperature (Frank _et al._, 1973) and during the vegetative stage of wheat, the stomata close at high water potential, but stomatal opening is ensured during reproductive stage at lower total water potentials (Teare _et al._, 1980). Hence, the critical value of XWP in wheat representing water stress is different for different growth stages.

The diurnal changes in XWP of wheat at flowering stage under N levels, tillage methods and water stocks (Fig.8 and 9) showed that it was almost the same at 0800h under different levels of N (Fig.8a, 9a). The values at 1700h were also similar under N levels, but were lower than the values at 0800h. This could be ascribed to the fact that due to no evaporative demand during night and almost negligible at 0800 and 1700h the internal gradients disappeared. There was progressive development of stress or decrease in XWP after 0800h till 1300h under N levels, tillage methods and water stocks. This was due to higher evaporative demand at 1300h and the rate of water uptake was inadequate to meet this demand. Xylem water potential was the lowest in the afternoon (1200 to 1300h) and the highest at 0800h under N levels, tillage methods and water stocks. Similar findings have also been reported by Nagarajarao (1984) and Singh et al. (1984). The level 40 kg N ha^{-1} maintained more negative XWP than 80 and 120 kg N ha^{-1} from 1000 to 1600h during the year 1989-90 and till 1300h during 1990-91. This could be due to less root growth under N_{40} (Tables 7, 8 and 9) which did not maintain higher water uptake to commensurate with evaporative demand. The second possible reason could be the role of N nutrition to regulate the plant water relations (Shimshi, 1970; Upreti and Sirohi, 1986). The decrease in XWP with time was more during the year 1990-91 possibly due to comparatively higher evaporative demand (Appendix II).

The diurnal changes in XWP under tillage methods (Fig. 8b, 9b) showed that XWP was also the same at 0800h under both the methods. Beyond this, the value of XWP at every time of the day was low under conventional tillage (T_1). This may be ascribed to the fact that root growth was less under T_1 than T_2 (Tables 7, 8 and 9). Mooris and Dayanard (1978) noted that in dense soil leaf water potential declined more rapidly because of restricted root growth. During the year 1990-91, there was not much difference in XWP under the tillage methods owing to no water stress at any time of the day as the rainfall distribution was more uniform during the second year of study. As the water stocks were not variable, the diurnal changes in XWP did not follow any consistent trend with respect to water stocks (Fig. 8c).

The leaf diffusion resistance (LDR) decreased with increase in application of N at maximum tillering and flowering stages of wheat growth during both the years of study (Table 12). The first year of study reflected significant effect of N at both the growth stages but during the second year, the effect was significant only at flowering stage. The level 120 kg N ha^{-1} maintained 30.7 and 28.3 per cent lower LDR over 40 kg N ha^{-1} during the year 1989-90; 13.2 and 24.5 per cent during 1990-91 at maximum tillering and flowering stages, respectively. The lower LDR at higher N level (120 kg N ha^{-1}) was due to higher XWP. Several investigators Van Bavel, 1967; Szeica and Long, 1969; Sandhu and Horton, 1977) have reported that LDR is closely related to plant water status. The higher LDR at 40 kg N ha^{-1} could be due to increase in root resistance to water flow in wheat plant owing to decrease in hydraulic conductivity. Similar observations have also been made by Shimshi (1970) for cotton plants and Radin and Boyer (1982) for sunflower plants. The decrease in LDR with increasing application of N could be related to increase in root growth (Tables 7, 8 and 9) resulting in higher water uptake (Appendix III).

Leaf diffusion resistance was lower under deep ploughing (T_2) at both the growth stages during both the years of study (Table 12). The significant effect of tillage methods, however, was only at flowering stage during the year 1989-90. The tillage method T_2 maintained 16.0 and 11.3 per cent lower LDR over T_1 during 1989-90; 12.0 and 12.1 per cent during 1990-91 at maximum tillering and flowering stages, respectively. The lower value of LDR under T_2 could be ascribed to the beneficial effects of deep ploughing (Table 2) on the modification of soil physical properties which resulted in higher moisture availability and better root growth (Yumura and Ishihara, 1971; Allamaras et al., 1977; Acharya and Bhagat, 1984; Bhadoria, 1988). As the variable water stocks could not be achieved in the field, hence there was no effect of water stocks on LDR (Table 12). Leaf diffusion resistance was higher at flowering stage in comparison to maximum tillering stage, under N levels, tillage methods and water stocks. Increase in LDR with ageing of plant may be due to increase in resistance to flow of water as plant aged (Anonymous, 1977; Samui and Kar, 1981).

The crop canopy is the integral part of the crop stand which acts as a site for various physiological processes and gives better indication of water status in plants. When the evapotranspiration (ET) is reduced following the development of water deficit in plant, the energy saved in the process of ET is partly diverted to raise the temperature of leaf. Thus, the crop canopy minus air temperature difference known as stress degree days (SDD) increases. The summation of SDD known as cumulative stress degree days (CSDD) was higher at N_{40} (Fig. 10a). In general, the CSDD decreased with time, both under N levels and tillage methods (Fig.10a, b). This trend, however, was not exactly increasing or decreasing. The level 120 kg N ha^{-1} maintained lower CSDD than 40 and 80 kg N ha^{-1}

levels because of better root growth which extracted higher amount of water, maintained higher XWP (Table 11a) and kept the canopy cooler than 40 and 80 kg N ha^{-1}. Similar observations were also made by Seligman et al. (1983) and Gajri and Prihar (1985). The crop canopy minus air temperature difference has been related to leaf water potential in wheat (Ehrler et al., 1978a; Singh and Singh, 1984). Increasing drought decreased leaf water potential and increased canopy minus air temperature accordingly (Ehrler et al., 1978b).

The stress degree days and CSDD under tillage methods during the years 1989-90 and 1990-91 (Fig.10b) did not differ during the period under study. But during the year 1989-90 the CSDD were higher than the values in 1990-91. This could be ascribed to more uniform distribution of rainfall during the year 1990-91. It indicated that the use of SDD for stress evaluation is applicable only when the stress is appreciable. Arora et al. (1991) reported that the canopy temperature of wheat under deep tillage treatment (30 cm) was 2-3°C lower because of higher water uptake than the crop where tillage was done upto 10 cm depth.

The relationship between soil moisture storage and various plant water status parameters viz., RLWC, XWP and LDR showed that these are affected by N and tillage methods (Table 13 and Fig. 11a,b,c). Relative leaf water content and XWP increased, but LDR decreased linearly with increase in profile moisture storage both under N levels and tillage methods. The increase in RLWC and XWP with increase in profile moisture content can be ascribed to higher moisture availability, variable root growth under N levels and tillage methods (Tables 7, 8 and 9) resulting in differential water uptake (Appendix III).

Leaf diffusion resistance decreased linearly with profile moisture storage (Table 13 and Fig. 11c). This may be due to increase in RLWC and XWP. Decreased soil moisture leads to decreased leaf water potential and increased resistance to movement of water (Boyer, 1968; Acevedo _et al._, 1971). The degree of correlation under N levels was good for XWP followed by LDR and least for RLWC. This suggested that XWP is more sensitive to the changes in soil water content. Under tillage methods the correlation was stronger for RLWC in comparison to XWP and LDR.

Relationship between soil water potential and plant water relations (Table 14 and Fig.12a,b,c) showed that RLWC and XWP increased, whereas LDR decreased linearly with increase in soil water potential both under N levels and tillage methods. Bharabme _et al._ (1984) also found positive and significant correlation between soil water potential and XWP of wheat under different levels of N.

Leaf diffusion resistance decreased linearly with increase in soil water potential both under N levels and tillage methods (Table 14 and Fig.12c). The decrease in LDR is attributed to increase in plant water status (Fig.12a,b). Katerji _et_ _al._ (1985) noted that from boot to grain formation stage of wheat, stomatal diffusion resistance depends principally on soil water availability. But from grain formation to milk ripe, stomatal diffusion resistance depended principally on plant water status irrespective of soil moisture. A study by Oosterhuis and Walker (1987) revealed that at the onset of water stress in wheat, stomatal diffusion resistance showed a clear increase which coincided with change in leaf water potential. The degree of correlation between soil water potential and plant water relations was stronger for XWP than for RLWC and LDR under N levels and tillage methods. This indicated that XWP is a better indicator of plant water status and responds more quickly to changes in soil water potential.

The relationship between XWP and RLWC (Table 15 Fig.13a) showed that RLWC increased with increase in XWP, both under N levels and tillage methods. At XWP of -18 bar, RLWC ranged from 72 to 76.8 per cent with increase in N from 40 to 120 kg N ha^{-1}. Similarly, under tillage methods, T_1 and T_2, RLWC ranged from 72.8 to 74 per cent. Similar relationship has also been reported by Kramer (1963) who reported that RLWC is the best indicator of plant water status and has been found to be closely correlated with water potential of the same tissue. Tomar and Ghildyal (1973a) noted that LWP of rice decreased sharply as RLWC decreased below 100 per cent. In the intermediate RLWC range, the drop in LWP was gradual, but below RLWC of 35 per cent, the drop in LWP was again very sharp.

Relative leaf water content decreased linearly with the increase in LDR (Table 15 and Fig.13b) both under N levels and tillage methods. Relative leaf water content ranged from 72.6 to 78.0 per cent with N levels increasing from 40 to 120 kg ha^{-1} at LDR of 4 s cm^{-1}. Similarly, under tillage methods, T_1 and T_2, RLWC ranged from 73.8 to 75.0 per cent at LDR of 4 s cm^{-1}. Several investigators (Van Bavel, 1967; Szeica and Long, 1969; Sandhu and Horton, 1977) have reported that LDR is closely related to plant water status. The correlation was good under N levels than tillage methods suggesting that the RLWC is more affected by N.

The relationship between XWP and LDR (Table 15, Fig.13c) showed that LDR is influenced by N levels and tillage methods. Leaf diffusion resistance decreased linearly with increase in XWP. At higher value of XWP, LDR ranged from 3.28 to 2.09 s cm^{-1} with N levels increasing from 40 to 120 kg ha^{-1}. Similarly, under tillage methods, T_1 and T_2, LDR ranged from 2.75 to 2.46 s cm^{-1}. The correlation was almost equally good both under N levels and tillage methods suggesting that LDR is equally affected by both. The relationship between stomatal resistance and leaf water potential is not single valued, it is modified by soil moisture, radiation and plant age (Tomar and O'Toole, 1982).

Growth of crop expressed in terms of leaf area index (LAI), accumulation of dry matter at different growth stages and crop yield at harvest was appreciably affected by N levels and tillage methods (Tables 16a and 17). Leaf area index significantly increased with the application of N at all the growth stages during both the years of study (Table 16a). The N level of 120 kg ha^{-1} gave 27.6 and 28.1 per cent higher LAI over 40 kg ha^{-1} during 1989-90; 65.3 and 41.3 per cent during 1990-91, at maximum tillering and flowering stages, respectively. This may be attributed to an increase in number of tillers per metre row length, number of leaves and leaf size. Higher LAI at 120 kg N ha^{-1} may be attributed to better root growth which could help in higher water and nutrient uptake and thereby extensive vegetative growth. Significant increase in LAI due to application of N has also been reported by several workers (Mann, 1957; Srivastava, 1968; Shrotriya and Misra, 1977; Reddy and Bhardwaj, 1982a).

Numerically the LAI was higher under deep ploughing (T_2) in comparison to conventional tillage (T_1) at all the growth stages during both the years of study (Table 16a). The significant effect, however, was only during the first year of study. The tillage method T_2 gave 20.1 and 13.6 per cent higher LAI over T_1 during 1989-90; 8.6 and 5.6 per cent during 1990-91 at maximum tillering and flowering stages, respectively. The increase in LAI under deep ploughing (T_2) could be ascribed to deep penetration of roots and higher rooting density, resulting in more uptake of water and nutrients which produced more extensive vegetative growth. Similar observations were also made by Hsiao (1973) and Arora et al. (1991). As the distinct variable water stocks could not be achieved in the field, there was no significant effect on LAI with respect to water stocks (Table 16a) at any growth stage (1989-90).

Leaf area index at maximum tillering (Table 16b), increased with N application, both under T_1 and T_2 during the year 1989-90. The treatment $N_{120}T_2$ was significantly superior over the treatments of $N_{40}T_1$, $N_{40}T_2$ and $N_{80}T_1$. This could be attributed to better root growth under $N_{120}T_2$ combination (Tables 7, 8 and 9) resulting in higher water uptake (Appendix III) and nutrient uptake (Table 19) which resulted in greater vegetative growth.

Dry matter production at different growth stages and at harvest (grain as well as straw yield) increased with N application during both the years of study (Table 17). The increase in dry matter production may be due to increase in number of tillers or shoots per metre row length, number of leaves, plant height and leaf area index. Similar observations have also been reported by Shrotriya and Misra (1977), Chaudhary and Sherif (1982), Sharma (1983) and Singh (1990). Significant increase in grain and straw yield with N application has also been reported by several workers (Patil and Batkal, 1975; Jat et al., 1976; Rathore and Singh, 1977;

Agarwal and Moolani, 1978; Singh and Sharma, 1979; Tomar *et al.*, 1979; Singh, 1990). The level of 120 kg N ha^{-1} gave 70.5, 82.9 and 38.6 per cent higher dry matter yield over 40 kg N ha^{-1} during the year 1989-90; 83.3, 39.7 and 42.5 per cent during 1990-91 at crown root initiation, maximum tillering and flowering stages, respectively. Similarly, at harvest the level 120 kg N ha^{-1} gave 42.2 and 35.6 per cent higher grain and straw yield, respectively during the year 1989-90. The corresponding values for the second year of study were 39.4 and 36.2 per cent.

The deep tillage (T_2) gave significantly higher dry matter yield at different growth stages and at crop harvest (grain and straw yields) during both the years of study (Table 17). The effect, however, was not significant during both the years at crown root initiation and at harvest in straw yield. The higher dry matter production under T_2 is ascribed to the favourable integrated effect of soil physical environment that enhanced root growth for greater uptake of water and nutrients and thus produced more plant height and number of ears per plant. Similar observations were also made by Chaudhary and Sherif (1982), Whitley and Dexter (1982) and Sharma and Acharya (1987). Besides water and nutrient uptake, roots can markedly influence the activities of shoots (Torey, 1976). The tillage method T_2 produced 10.9, 16.4, 15.0, 14.6 and 5.2 per cent higher dry matter over T_1 during

1989-90; 17.0, 14.2, 10.8, 13.8 and 4.2 per cent during the year 1990-91 at crown root initiation, maximum tillering, flowering and at harvest in the grain and straw yield, respectively. Deeper and denser root system in deep ploughing has been reported to extract more water from the soil during the reproductive phase resulting in increased yield of wheat (Bhagat and Acharya, 1988; Arora et al., 1991 and Gajri et al. 1991).

As the water stocks were not variable, there was no effect of water stocks on dry matter production (Table 17) at any growth stage and at crop harvest in grain and straw yields during both the years of study.

There was significant effect of N application on its content in plant at different growth stages and at harvest in grain and straw during both the years of study (Table 18). Application of N, enhanced its availability and absorption by plants. Increase in N content in grain and straw with the application of N has also been reported by Shrotriya and Misra (1977), Jat et al. (1976a), Sandhu and Gill (1976) and Singh (1990). Numerically, the N content was higher under deep ploughing (T_2) in comparison to conventional tillage (T_1) at all the growth stages during both the years of study (Table 15). But the effect of tillage methods was not significant at any growth stage, except in straw (1989-90), during both the years of study. These findings are in conformity with those of

Barbosa <u>et</u> <u>al</u>. (1989) who also did not find any significant difference in N content under various tillage practices. The higher N content in plant under T_2 may be attributed to improvement in soil physical environment resulting in better root growth and their penetration to deeper depths and hence greater access to subsoil moisture and nutrients. Since the variable water stocks could not be achieved in the field, there was no effect on N content due to water stocks at different growth stages and at harvest in grain and straw (Table 18).

Nitrogen uptake in plant, at different growth stages and at harvest in grain and straw (Table 19), showed that it increased significantly with N application during both the years of study. Increase in N uptake was due to increase in dry matter production (Table 17) at different growth stages and at harvest in the grain and straw yields together with higher N concentration. Increase in N uptake in wheat with the application of N has also been reported by several other workers (Shekhawat <u>et</u> <u>al</u>., 1975; Sinha, 1975; Sandhu and Gill, 1976; Sharma, 1983; Singh, 1990). Nitrogen uptake was significantly higher under deep ploughing (T_2) at each growth stage during both the years of study except crown root initiation and at harvest in straw (1990-91). This was due to higher dry matter production under T_2. Secondly, the higher uptake under T_2 could be due to improvement in soil structure in the rhizosphere (better soil physical environment) which resulted in better root growth that facilitated more removal of N (Nielsen and Humphries, 1966; Terman et al., 1976; Chaudhary and Sandhu, 1983; Rehman and Islam, 1986 and Sharma and Acharya, 1987).

The foregoing discussion suggests that the application of 120 kg N ha^{-1} in combination with deep ploughing had favourable effect on plant growth and water production functions during both the years of study. Deep ploughing lowered the bulk density and in combination with higher level of N resulted in better root growth and development. This helped in the extraction of water from subsurface depths and thereby maintained higher plant water status, i.e. higher RLWC and XWP, and low LDR and SDD. Integrated effect of better root growth was reflected in efficient water and nutrient uptake, higher LAI and dry matter production at different growth stages and at crop harvest during both the years of study. Various indices of plant water status showed good agreement with soil moisture storage and soil water potential, both under N levels and tillage methods.

SUMMARY

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The studies entitled "Profile water extraction through water-nitrogen-tillage interaction in wheat" were carried out at the experimental farm of Himachal Pradesh Krishi Vishvavidyalaya, Palampur (Kangra). The experiment was laid out in Split Plot Design with 18 treatments, consisting of combinations of three levels of N (40, 80 and 120 kg ha^{-1}), two tillage methods viz., conventional tillage (T_1) and deep ploughing (T_2) in main plots and three variable water stocks viz., W_1, W_2 and W_3 in subplots. The experiment had three replications and plot size was 5x2 m. Wheat (VL-421) was used as a test crop. The studies were aimed at evaluating the effect of these treatments on water extraction pattern, water production functions viz., relative leaf water content (RLWC), xylem water potential (XWP), leaf diffusion resistance (LDR) and stress degree days (SDD), root and plant growth, nutrient content and uptake. Relationship of soil moisture storage, soil water potential with water production functions, and inter-relationships among themselves have also been evaluated. The results obtained are summarized in the subsequent paragraphs.

The texture of the experimental site was silty clay loam. The clay content was higher in 30-45 cm (32.9%) and 15-30 cm (32.2%) depths in comparison to 0-15 cm (29.4%) and other depths (23.8 - 31.5%). The bulk density increased with depth and the subsurface depth of 75-90 cm had comparatively higher bulk density (1.36 Mg m^{-3}) in comparison to the surface depth of 0-15 cm (1.10 Mg m^{-3}). The deep tillage (T_2) treatment lowered bulk density at surface and subsurface depths during both the years of study at sowing of the crop.

The water retention in the 0-15 and 15-30 cm depths was poor in comparison to subsurface depths. The depth of 75-90 cm retained the highest and 0-15 cm depth the lowest amount of water at any value of suction. Field determined hydraulic conductivity values showed that the layers 0-15-30-45 cm were slightly less permeable than the subsurface layers of 45-60-75-90 cm. The saturated hydraulic conductivity decreased with depth.

The decrease in soil water content and changes in hydraulic gradients were maximum upto 30 cm depth under the treatments of $N_{40}T_1$ and $N_{40}T_2$ and upto 45 cm depth under the remaining treatments. This suggested that under low fertility level water needs were met by the layers upto 30 cm, whereas by the layers upto 45 cm under the recommended fertility level. The changes in hydraulic flux across 82.5 cm depth showed that the flux remained downward for most of the time under the treatments of $N_{40}T_1$ and $N_{40}T_2$ and became upward at the end of drying period (during 160 to 165 DAS). Under the remaining treatments, the flux became upward between 145 to 150 DAS, but after that remained near to zero line of flux.

The root water uptake (r_z) from different depths showed that the treatments of $N_{40}T_1$ and $N_{40}T_2$ extracted maximum amount (85%) of water from 0-15 and 15-30 cm depths and very less quantity from 30-45 cm depth. The depthwise extraction of water under these two treatments decreased with depth. Under the remaining treatments about 75-80 per cent of total water was extracted from 0-45 cm depth. There was, however, no well defined trend for the water uptake with respect to depth. The total water uptake (R_z) which also includes evaporation, increased with increase in N levels both under conventional tillage (T_1) and deep ploughing (T_2). The maximum uptake of water was under the treatment of $N_{120}T_2$ (0.392 cm d^{-1}) and the lowest under $N_{40}T_1$ (0.135 cm d^{-1}).

The per day water withdrawal calculated by the method of Ogata <u>et</u> <u>al</u>. (1960) and from profile depletion (ΔS_z) showed that the hydraulic flux at the lower boundary of the profile should be adjusted in the latter as its magnitude during the complete life cycle of the crop is appreciable.

Root growth (root mass density, root volume and root length density) determined at different growth stages, and at harvest, increased with the application of N and was higher under T_2 during both the years of study. The maximum root growth was obtained at recommended fertility level (120 kg N ha^{-1}) and under tillage method T_2.

The relative leaf water content (RLWC) determined at maximum tillering and flowering stages of wheat growth increased with the application of N during both the years of study. The effect of N levels was significant at both the growth stages during 1989-90 and only at flowering stage during 1990-91. The deep tillage, T_2, maintained higher RLWC, but its effect was significant only at flowering stage (1989-90).

Xylem water potential (XWP), determined at three important growth stages, increased with N application. The effect was significant at all the growth stages during first year of study and only at flowering stage during 1990-91. The XWP was higher under T_2, but the effect was significant only at maximum tillering and flowering stages during the year 1989-90.

The diurnal changes in XWP at flowering stage of wheat growth showed that it was almost the same at 0800h under N levels, tillage methods and water stocks, but the values were quite higher during the second year of study. Similarly, at 1700h the values were also the same, but the second year of study showed higher XWP. The lowest XWP was observed from 1200 to 1300h. The changes were rapid in the morning and evening hours in comparison to major part of the day. The XWP started recovering after 1300h, but the recovery was not upto the values observed at 0800h.

Leaf diffusion resistance (LDR), determined at maximum tillering and flowering stages of wheat growth, decreased with increase in N dose. There was significant effect of N at both the growth stages during the year 1989-90 and only at flowering stage during 1990-91. The deep ploughing (T_2) maintained lower LDR than conventional tillage (T_1), but the effect was significant only at flowering stage during 1989-90.

The stress degree days (SDD) were recorded from 102 to 169 DAS during 1989-90 and 85 to 171 DAS during 1990-91. The level 120 kg N ha^{-1} maintained lower SDD than 40 and 80 kg N ha^{-1} The cumulative stress degree days (CSDD) steadily decreased with time under all the levels of N and tillage methods. CSDD were higher under N_{40}, but there was not much difference under N_{80} and N_{120}. There was no difference in CSDD under tillage methods, but during 1989-90 CSDD were higher than during 1990-91. In general, the crop was not under stress(neither under N levels nor under tillage methods)as the values of CSDD were always negative.

The relationship of different water production functions viz., RLWC, XWP and LDR with soil moisture storage at flowering stage of wheat growth showed that under N levels, the XWP was more affected by soil water content whereas RLWC under tillage methods. Similarly, both under N levels and tillage methods, XWP showed better correlation with soil water potential, suggesting that it is more affected by soil water potential.

The inter-relationships between different water production functions showed better correlation between XWP and LDR, both under N levels and tillage methods.

The leaf area index, recorded at maximum tillering and flowering stages, increased significantly with increase in N levels. The deep tillage method, T_2, maintained higher LAI, but the significant effect was observed only during the first year of study.

The dry matter production recorded at different growth stages, viz., crown root initiation, maximum tillering, flowering and at crop harvest (grain as well as straw yield) significantly increased with N application during both the years of study. The grain and straw yield increased significantly with increase in N levels during the first year of study. But, during the year 1990-91, the significant increase in crop yield (grain as well as straw yield) with N levels was only upto 80 kg N ha^{-1}. It further increased with N application, but the increase was not significant. The tillage method T_2 showed higher dry matter yield at different growth stages and at harvest. The effect, however, was significant at maximum tillering, flowering and at crop harvest in grain.

Nitrogen uptake and its content increased with N application and the effect was significant at all the growth stages and at crop harvest in grain and straw, during both the years of study. The tillage method T_2 showed higher N content and its uptake at every growth stage.

Since the variable water stocks could not be achieved in the field due to frequent rains during both the years of study, their effect on plant and root growth was not discernible. There was no effect on either of the water production functions studied. The same was true for dry matter production at different growth stages and in grain and straw yields at harvest of crop.

CONCLUSIONS

The study brought out that the higher level of N and deep tillage resulted in water extraction from subsurface depths and maintained higher plant water status, lower LDR and SDD thus giving higher crop yield. Under the situation, like ours in the state, where wheat is mostly grown as a rainfed crop, it is important that subsoil moisture is judiciously utilized by the crop. The interaction of deep tillage and higher level of N upto 120 kg ha^{-1} encouraged greater root growth and helped in higher extraction of subsoil moisture and thereby increased the grain and straw yield. During the dry periods, there is considerable upward flux from lower layers, the magnitude of which is not to be ignored while making the field water balance.

Among different water productions, the XWP showed better relationship with profile water status and profile water potential. The crop canopy minus air temperature difference, i.e. SDD is quite sensitive to changes in plant water status and is a good and precise index for evaluating the drought resistance of different varieties and plant species. This is much easier to measure and interpret.

The study brought out that the application of 120 kg N ha^{-1} (the recommended dose) is essential for proper root and shoot growth. The deep tillage checks weed growth, lowers down the mechanical impedence and creates favourable air-water relations for growth and proliferation of roots.

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*Original not seen

APPENDICES

APPENDIX I: Daily rainfall, pan evaporation and average temperature (maximum and minimum) during the crop growing season (1989-90)

Days after sowing	Rain-fall (mm)	Pan Evapo-ration (mm)	Temperature °C		Days after sowing	Rain-fall (mm)	Pan evapo-ration (mm)	Temperature °C	
			Max.	Min.				Max.	Min.
1	2	3	4	5	6	7	8	9	10
1 (6$\frac{11}{89}$)	-	2.7	18.7	8.0	45	36.9	2.3	13.0	9.4
2	-	2.6	19.2	7.2	46	1.0	0.5	11.1	5.0
3	-	2.3	20.3	8.0	47	35.3	0.5	13.6	5.5
4	-	2.5	20.9	9.0	48	-	0.5	13.7	5.0
5	-	2.9	22.1	10.6	49	-	1.2	13.4	4.4
6	-	3.4	23.2	11.5	50	-	0.5	12.7	4.8
7	-	3.1	23.3	12.9	51	-	1.4	12.5	2.6
8	-	2.7	22.4	12.5	52	-	1.5	13.7	2.5
9	-	3.0	22.0	11.5	53	-	1.3	14.7	3.1
10	-	2.6	21.7	9.9	54	-	1.1	14.8	3.7
11	-	2.4	21.2	9.4	55	-	0.4	13.3	4.5
12	-	3.0	21.3	9.5	56	-	1.5	13.7	2.5
13	-	1.5	20.7	11.0	57 (1$\frac{1}{90}$)	-	1.1	13.8	3.4
14	-	2.4	20.5	10.0	58	-	0.9	13.2	3.0
15	-	2.8	21.0	9.7	59	-	1.8	14.6	3.5
16	-	2.4	20.8	9.5	60	-	1.0	14.7	6.0
17	9.2	3.2	20.5	9.3	61	-	2.0	14.8	4.6
18	0.1	2.0	19.3	9.4	62	9.2	1.5	15.3	5.7
19	29.8	3.3	17.1	10.3	63	-	1.4	15.0	5.6
20	6.3	1.7	14.5	8.6	64	-	1.3	15.3	4.4
21	-	1.4	15.0	6.0	65	-	1.4	16.4	3.4
22	-	1.3	17.2	6.6	66	-	2.8	18.7	6.5
23	-	1.7	17.3	7.0	67	-	3.0	19.7	7.1
24	-	1.4	17.1	6.5	68	-	2.6	20.7	8.6
25	-	1.3	17.7	6.0	69	-	2.0	21.1	9.4
26	-	1.2	18.2	6.6	70	-	2.7	19.9	8.5
27	-	2.3	18.1	6.4	71	-	2.0	19.8	5.6
28	-	1.9	19.0	7.2	72	-	2.1	19.7	9.6
29	-	1.9	19.4	6.6	73	-	1.8	19.3	8.1
30	-	1.1	18.4	6.5	74	-	1.3	18.3	11.0
31	-	1.0	16.7	7.2	75*	-	2.2	18.9	9.5
32	-	1.3	16.5	9.2	76	-	2.2	21.0	10.6
33	-	2.0	17.8	9.5	77	-	1.2	20.4	11.5
34	-	1.4	18.1	8.6	78	-	1.9	19.7	9.5
35	-	1.2	16.1	6.9	79	-	1.4	20.0	8.4
36	-	1.5	15.4	6.2	80	-	1.7	20.4	8.0
37	-	1.6	16.3	5.4	81	-	1.8	20.4	8.0
38	-	1.6	16.6	5.6	82	-	1.9	19.0	9.5
39	-	1.3	16.9	5.1	83	18.2	4.5	18.2	10.0
40	-	1.2	16.5	6.0	84	-	0.6	16.5	7.4
41	-	1.6	16.8	7.6	85	0.7	0.7	15.3	7.0
42	-	1.9	17.5	8.1	86	-	1.6	16.5	6.5
43	-	1.6	15.9	7.0	87	3.7	1.9	16.8	8.3
44	32.0	1.6	15.2	9.4	88	1.1	1.8	16.0	5.9

contd...

APPENDIX I : Contd...

1	2	3	4	5	6	7	8	9	10
89*	-	2.0	16.2	4.0	140	-	3.5	15.5	4.5
90	-	1.3	16.9	7.0	141	-	3.8	17.7	6.4
91	-	2.6	13.2	7.7	142	-	3.2	18.3	8.0
92	-	1.3	17.0	6.2	143	5.9	2.2	16.0	7.0
93	2.1	1.7	16.1	7.5	144	12.2	3.8	16.4	5.5
94	38.0	4.0	15.5	9.5	145	-	2.4	16.1	7.5
95	25.6	3.9	14.5	8.0	146	2.2	1.4	16.6	7.5
96	-	2.3	17.9	7.0	147	2.0	4.2	18.7	6.5
97	0.2	1.1	17.7	9.7	148	-	3.7	18.7	6.5
98	-	1.1	16.6	7.0	149	-	4.0	20.2	9.0
99	21.7	2.7	15.7	9.3	150	-	4.1	21.5	9.5
100	57.5	2.1	12.7	7.2	151	-	4.0	22.4	10.6
101	-	2.2	12.4	5.1	152	15.0	2.0	20.6	13.6
102	-	2.4	15.4	4.6	153	10.9	4.5	19.7	10.2
103	-	2.6	15.7	3.3	154	-	5.2	21.5	11.3
104	-	0.8	14.3	5.6	155	-	5.3	22.3	10.0
105	-	0.5	12.1	4.7	156	-	6.2	23.5	10.8
106	-	1.7	13.0	3.9	157	-	6.4	26.0	15.5
107	0.3	1.6	14.8	5.0	158	10.3	5.3	26.0	17.5
108	-	1.4	15.3	4.7	159	-	3.9	23.8	10.0
109	-	1.8	16.0	4.5	160	-	4.7	22.5	12.5
110	3.7	2.2	16.0	5.5	161	-	3.8	23.7	12.5
111	5.0	1.0	14.3	7.0	162	1.0	3.8	23.7	14.2
112	23.1	1.1	11.2	6.0	163	-	4.5	25.5	15.5
113	1.5	2.4	11.2	5.0	164	-	6.9	27.8	18.2
114	26.0	2.4	11.7	6.3	165	-	7.0	28.1	15.0
115	8.5	2.2	10.8	4.0	166	-	7.0	27.8	14.4
116	-	1.9	13.2	3.5	167	-	9.6	28.2	14.5
117	-	2.5	14.7	1.8	168	-	8.2	29.5	17.4
118	-	0.8	15.6	3.5	169	-	7.8	29.6	19.5
119	-	2.7	16.4	5.0	170	-	7.6	29.7	16.5
120	-	1.5	16.5	6.4	171	-	9.1	30.8	18.1
121	-	2.6	17.0	5.0	172	-	5.8	30.0	20.2
122	-	3.1	18.5	6.1	173	-	8.2	28.3	18.2
123	-	2.9	20.2	7.5	174	-	6.4	27.5	14.2
124	-	3.9	20.7	9.2	175	-	5.4	26.4	14.8
125	-	3.1	19.1	9.0	176	-	6.6	27.5	15.9
126	1.3	1.5	16.6	10.0	177	-	6.5	27.7	16.0
127	-	3.3	17.4	7.5	178	0.5	5.8	27.3	17.9
128	-	2.9	19.8	8.1	179	-	4.8	27.5	15.1
129	-	3.3	20.8	9.1	180	0.5	4.2	27.1	16.6
130	-	2.0	20.9	10.4	181	0.6	3.0	25.4	14.5
131	-	2.2	21.0	10.7	182	13.4	7.4	25.4	14.9
132	28.0	1.7	21.9	12.4	183	-	3.5	26.2	15.9
133	25.0	2.8	20.3	10.0	184	-	4.4	26.6	16.5
134	29.5	3.7	17.2	11.5	185	-	4.8	28.3	19.4
135	16.6	5.4	15.9	9.2	186	6.2	5.0	29.3	11.0
136	56.7	3.2	16.0	9.2	187	-	6.4	29.8	18.5
137	19.2	3.6	15.3	10.0	188	24.2	4.0	28.5	18.3
138	0.8	1.7	15.3	6.1	189	-	5.2	28.1	16.4
139	0.6	1.0	15.0	5.8	190**	-	4.4	29.4	19.3

*Water stocks made variable in 0 to 90 cm depth

**Crop harvested

APPENDIX II: Daily rainfall, pan evaporation and average temperature (maximum and minimum) during the crop growing season (1990-91)

Days after sowing	Rain fall (mn)	Pan Evapo-ration (mm)	Temperature °C Max.	Min.	Days after sowing	Rain fall (mm)	Pan evapo-ration (mm)	Temperature °C Max.	Min.
1	2	3	4	5	6	7	8	9	10
1 (6-11-90)	-	2.6	22.8	11.2	45	-	2.1	18.2	6.0
2	-	2.5	22.2	11.2	46	-	1.6	16.7	5.3
3	-	2.6	22.1	11.0	47	-	1.7	17.7	5.1
4	-	2.5	21.7	11.3	48	-	1.8	17.8	4.5
5	-	3.2	22.2	11.0	49	-	1.9	16.3	5.3
6	-	4.2	23.8	11.3	50	-	2.0	16.8	6.8
7	-	3.5	24.1	12.5	51	-	1.9	18.1	7.0
8	-	3.2	24.0	11.6	52	8.9	2.7	18.5	8.4
9	-	3.3	24.0	12.2	53	40.5	0.2	16.2	8.0
10	-	3.1	23.5	11.4	54	76.8	0.7	12.7	8.3
11	-	3.0	23.3	11.5	55	56.3	0.2	7.7	-0.1
12	-	3.2	22.7	10.8	56	-	1.0	6.0	-0.5
13	-	3.6	22.6	10.5	57 (1-1-91)	1.1	1.1	6.7	0.0
14	-	3.3	22.7	10.4	58	1.2	1.2	9.2	0.0
15	-	1.8	21.7	10.4	59	-	1.8	12.0	0.9
16	1.0	2.8	20.0	9.4	60	-	1.9	12.9	2.9
17	2.4	1.6	16.8	8.9	61	-	2.2	13.8	1.5
18	-	2.5	17.5	8.5	62	-	1.1	13.5	3.1
19	-	2.9	19.5	7.9	63	5.0	2.0	12.7	5.7
20	-	3.1	20.7	8.2	64	-	0.9	11.7	5.2
21	-	2.8	20.9	8.6	65	-	1.8	13.6	3.5
22	-	2.1	19.9	8.4	66	-	1.7	15.0	4.0
23	-	2.6	19.2	7.2	67	-	0.7	12.5	4.9
24	-	2.8	19.8	7.2	68	-	1.7	11.5	3.2
25	-	2.7	20.1	7.5	69	2.1	1.0	12.0	2.0
26	-	2.6	19.7	7.5	70	-	1.1	10.8	0.5
27	-	2.3	19.2	7.0	71	-	1.7	11.7	0.8
28	-	2.6	18.6	6.9	72	-	1.3	11.6	4.0
29	-	2.5	18.0	6.5	73	-	1.7	12.3	2.4
30	-	2.4	18.1	6.1	74	-	1.2	13.7	3.3
31	-	2.1	18.2	7.3	75*	-	1.6	13.7	1.5
32	-	2.5	18.5	7.5	76	-	2.0	14.4	2.5
33	-	2.0	17.0	8.4	77	-	2.8	14.6	3.4
34	-	1.8	16.7	8.0	78	-	2.2	14.8	2.9
35	-	1.8	16.4	5.0	79	-	2.1	14.9	3.9
36	-	2.4	17.5	6.4	80	-	2.4	16.2	4.1
37	-	2.0	18.4	7.6	81	-	1.6	17.0	8.4
38	-	2.4	18.5	6.9	82	-	2.3	17.5	9.0
39	9.7	1.6	16.6	6.2	83	-	2.8	20.7	11.4
40	31.2	0.7	11.0	5.8	84	1.7	3.0	21.0	13.0
41	33.4	0.3	13.0	6.5	85	-	1.7	20.1	9.6
42	-	2.0	15.2	5.4	86	-	1.6	18.2	4.8
43	-	2.3	17.9	6.3	87	-	2.9	17.3	6.4
44	-	2.4	18.7	6.9	88	-	2.5	17.1	5.4

contd...

APPENDIX II: Contd...

1	2	3	4	5	6	7	8	9	10
89	-	2.1	16.7	5.1	138	3.3	2.7	19.5	7.9
90	-	2.3	15.7	6.5	139	-	3.5	17.9	6.0
91	-	2.6	15.2	4.7	140	-	3.8	19.4	6.0
92	-	2.5	15.2	6.0	141	-	4.6	21.2	9.7
93	2.4	1.3	14.7	9.1	142	-	4.5	23.3	11.5
94	-	2.3	15.5	6.4	143	-	4.6	25.0	13.3
95	-	3.2	17.6	7.5	144	--	5.8	26.6	13.1
96	6.5	1.1	17.5	10.5	145	-	5.8	27.2	15.3
97	21.0	3.1	16.1	9.0	146	-	7.0	27.4	15.0
98	43.3	3.3	13.1	6.7	147	8.9	7.2	27.2	17.4
99	-	2.4	12.7	4.4	148	4.2	7.0	26.9	13.0
100	-	1.4	15.1	4.4	149	2.1	3.7	24.9	11.5
101	-	1.8	14.7	4.3	150	-	3.7	23.2	12.5
102	-	1.8	14.5	4.5	151	-	4.4	24.3	13.0
103	-	2.4	15.1	2.4	152	2.3	3.6	24.1	13.1
104	-	3.3	15.1	2.0	153	-	3.6	22.5	12.5
105	-	3.4	15.9	4.3	154	20.1	5.9	21.6	12.6
106	-	3.3	17.9	4.6	155	1.5	2.8	18.5	9.5
107	-	3.0	18.8	9.0	156	3.1	3.4	17.6	9.1
108	-	3.2	20.3	10.4	157	-	3.5	21.1	9.5
109	-	4.1	21.3	10.5	158	0.3	2.5	22.1	12.5
110	1.9	3.8	18.7	10.2	159	39.3	0.9	20.2	12.5
111	14.7	2.5	16.1	10.0	160	3.0	1.9	19.2	10.3
112	47.1	3.5	16.7	8.7	161	-	3.3	18.7	10.6
113	2.0	1.0	16.2	5.3	162	-	4.7	20.2	10.0
114	1.3	1.8	14.4	5.6	163	-	4.9	20.6	8.1
115	-	2.4	14.7	5.6	164	-	5.6	22.5	9.3
116	-	3.5	16.9	4.0	165	-	5.0	24.8	11.6
117	2.5	2.4	16.7	7.5	166	-	5.0	25.8	13.1
118	3.2	1.9	15.6	7.1	167	-	6.2	27.0	14.8
119	24.6	3.1	15.2	9.0	168	10.9	6.0	26.9	15.3
120	-	2.0	15.7	5.7	169	2.1	6.1	25.0	11.8
121	-	2.4	16.7	5.0	170	-	5.7	25.0	13.9
122	-	2.5	18.0	6.2	171	-	6.7	27.0	14.3
123	6.8	1.5	18.1	10.4	172	-	6.9	27.5	15.9
124	-	2.4	18.5	10.7	173	-	5.7	27.8	16.4
125	-	3.6	21.0	11.3	174	-	6.0	28.5	16.1
126	-	4.0	22.2	10.9	175	-	7.1	29.3	15.9
127	-	3.3	22.7	11.3	176	-	7.3	29.7	16.5
128	34.7	2.1	17.9	9.7	177	4.0	4.6	29.4	17.3
129	-	4.1	17.0	7.5	178	3.4	5.6	27.8	16.0
130	-	4.3	21.3	9.0	179	-	5.5	27.5	15.2
131	-	3.9	22.6	12.5	180	-	7.0	28.9	16.3
132	-	4.6	23.5	12.5	181	-	3.8	29.3	20.6
133	5.8	4.4	24.3	15.5	182	-	5.4	29.4	16.4
134	-	3.2	23.1	13.0	183	-	7.6	30.2	18.5
135	-	3.6	22.5	11.0	184**	-	6.4	29.7	19.2
136	-	2.2	21.2	12.0					
137	9.4	4.1	20.6	10.6					

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* Water stocks made variable in 0 to 90 cm depth

** Crop harvested

APPENDIX III: Water uptake by crop roots at different depths under different levels of nitrogen and tillage methods during a typical drying period from 140 to 170 days after sowing

Treatments	Depth (cm)						
	15	30	45	60	75	90	R_z
Nitrogen levels (N)							
N_{40}	0.0043	0.0041	0.0014	-	-	-	0.147
N_{80}	0.0056	0.0077	0.0025	0.0019	-	-	0.266
N_{120}	0.0054	0.0064	0.0070	0.0021	0.0018	0.0015	0.363
Tillage methods (T)							
T_1	0.0050	0.0054	0.0038	0.0010	0.0005	0.0004	0.242
T_2	0.0055	0.0067	0.0034	0.0016	0.0007	0.0006	0.278

APPENDIX IV: Effect of nitrogen levels, tillage methods and water stocks on root mass density (mg $m^{-1} \times 10^{6}$) at different stages and harvest of wheat crop in 0-15 and 15-30 cm (figure in parentheses) depths

Treatments	1989-90			1990-91		
	Stages of wheat growth					
	MT	FS	AH	MT	FS	AH
Nitrogen levels (N)						
N_{40}	0.19 (0.01)	0.25 (0.04)	0.29 (0.06)	0.23 (0.02)	0.29 (0.06)	0.28 (0.07)
N_{80}	0.22 (0.02)	0.33 (0.05)	0.41 (0.06)	0.27 (0.03)	0.36 (0.05)	0.44 (0.08)
N_{120}	0.28 (0.03)	0.39 (0.07)	0.48 (0.09)	0.30 (0.03)	0.54 (0.07)	0.51 (0.08)
CD 0.05	0.03 (NS)	0.03 (0.01)	0.03 (0.02)	0.04 (NS)	0.13 (NS)	0.09 (NS)
Tillage methods (T)						
T_1	0.21 (0.02)	0.31 (0.05)	0.36 (0.07)	0.26 (0.02)	0.34 (0.05)	0.39 (0.07)
T_2	0.25 (0.02)	0.34 (0.06)	0.42 (0.08)	0.27 (0.03)	0.44 (0.06)	0.43 (0.08)
CD 0.05	NS (NS)	NS (NS)	NS (NS)	NS (NS)	NS (NS)	NS (NS)
Water stocks (W)						
W_1	0.24 (0.02)	0.30 (0.06)	0.38 (0.07)			
W_2	0.23 (0.03)	0.34 (0.05)	0.38 (0.07)			
W_3	0.23 (0.03)	0.34 (0.05)	0.43 (0.08)			
CD 0.05	NS (NS)	NS (NS)	NS (NS)			

MT=Maximum tillering, FS=Flowering stage, AH = At harvest

APPENDIX V: Effect of nitrogen levels and tillage methods on weed growth (dry weight, g m^{-2}) at 50 days after sowing (DAS)

Treatments	1989-90	1990-91
Nitrogen levels (N)		
N_{40}	18.4	15.8
N_{80}	25.1	20.8
N_{120}	34.7	32.0
CD 0.05	2.3	3.7
Tillage methods (T)		
T_1	28.5	26.2
T_2	23.5	19.5
CD 0.05	1.8	3.1