# Effective Management of Irrigation Water for Wheat Crop Under Stressed Conditions Using Simulation Modeling

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## Abstract

The reported study was undertaken to determine an efficient strategy for management of irrigation water in case of wheat crop under water stressed conditions in a sub-tropical sub-humid region. Field experiments were conducted on wheat crop over a period of three years with five different irrigation treatments. Layer-wise soil moisture status was continuously monitored to determine the crop water extraction pattern and thereby the irrigation management depth. Irrigation treatments consisted of different levels of depletion of available soil water. The five levels of depletions considered in the study were 10%, 30%, 45%, 60% and 75%. CERES- wheat growth simulation model was calibrated, validated and used for decision-making. In order to asses the depth and time variation of soil moisture under different scheduling of irrigation, soil moisture was measured periodically in 15-30, 30-45, 45-60, 60-90 and 90-120 cm soil profiles using a neutron probe, while the soil moisture in 0-15 cm soil profile was determined by gravimetric method. It was observed that the plants extracted most of the soil moisture from 0-45 cm soil layer in case of wheat. Therefore, it was recommended that only 0-45 cm of soil profile be considered for scheduling of irrigation in case of wheat crop grown in sandy loam soil in the sub-tropical regions under water scarcity conditions. The field water use efficiency of wheat crop was found to be the highest when irrigation was scheduled at 45% depletion of ASW. It was therefore recommended that under water scarcity condition, plant extractable soil water depletion of more than 45% of ASW must be avoided even during non-critical stages of the wheat crop grown in medium sandy loam soils in subtropical regions. The calibrated CERES- wheat model was found to be quite efficient in simulation of yield parameters and layer-wise soil moisture extraction pattern. It can therefore be successfully used for decision making in the region.

**Keywords**: CERES-Wheat model, validation, water balance, depletion level, water use efficiency.

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# I. Introduction

Wheat is one of the most important and popular major crops all over the world. Wheat is grown on an area of about 19-20 million hectares in India and nearly 54 percent of this area is irrigated. That constitutes about 27 percent of the irrigated area of the country. Well-drained clay loams, loams and sandy loams are suitable for this crop. Therefore, proper management of important inputs particularly irrigation water using modern technology is essential for increasing production and for giving high return to the farmers. Crop growth simulation models could be used as useful tools for determining crop growth, development and to formulate irrigation management strategies for efficient use of inputs (Dhanpal, 1992; Jeffery et al., 1994)

Wheat crop is quite sensitivity to water stress. Therefore, wheat crop needs frequent irrigation for good growth and yield. Past studies revealed that CERES group of crop growth models for maize, sorghum and wheat are suitable for decision making related to water management (Steiner et al., 1991).

In case of situations where water supply is limited, the irrigation demand of the entire cropping pattern cannot be met fully. In these conditions, deliberate under irrigation, also known as deficit irrigation can play a major role (Iqbal et al., 1999). By deficit irrigation, crops are purposefully under irrigated during plant growth stages that are relatively insensitive to water stress as regards to the quality and quantity of the harvestable yield (Musick, 1994). Identifying growth stages of a particular cultivar under local conditions of climate and soil fertility allows irrigation scheduling for both maximum crop yield and most efficient use of scarce water resources (Doorenbos and Kassam, 1979).

Rising cost of irrigation pumping, low commodity prices, inadequate irrigation system capacities and limited irrigation water supplies are among the reasons that prompt many irrigators to deliberately apply less water than is required to obtain maximum yield (Craciun and Craciun, 1999). The goal of effective management of irrigation water is to enhance economic returns with limited use of water and/or energy.
It is observed that proper scheduling of irrigation to supply adequate quantum of water during the moisture sensitive period of flowering and yield formation stages, yet allowing moderate stress at vegetative and maturity stages produce the optimum yield with maximum water use efficiency and water economy (Reddy and Reddy, 1993).

With these background considerations, a comprehensive field investigation was undertaken on a coarse textured lateritic soil at the experimental farm of Agricultural and Food Engineering Department, Indian Institute of Technology, Kharagpur, India, to study the effects of various scheduling of irrigation on the crop yield parameters under limited water availability conditions.

## Objectives

The specific objectives of the study were:

1. To study the effect of different schedules of irrigation on root zone soil water status, growth, yield parameters and water use efficiency of the wheat crop.

2. To recommend an effective irrigation water management strategy for wheat grown in sub-humid sub-tropical regions, particularly under water scarcity conditions.
3. To calibrate and validate CERES- wheat model for irrigation water management related decision-making in the aforesaid agro-climatic condition when adequate experimental data are not available.

## 2. Materials and Methods

### 2.1 Experimental site

Field experiments were conducted at the experimental farm of the Agricultural and Food Engineering Department, Indian Institute of Technology, Kharagpur, India ($22^0$ 19' N latitude and $87^0$19' E latitude). The local climate is sub-humid and sub-tropical with an average rainfall of 1200 mm concentrated over the months of June to September. The soil at the experimental site was an acid lateritic sandy loam. The soil is partly eroded due to high intensity rainfall in the area during monsoon season.

Comprehensive field experiments were carried out on wheat crop. Wheat is a 100-110 days cereal crop of the region and suits to the prevailing climate in the winter season (December to March) of the year. Experiments were conducted during three consecutive years such as: 1995-96, 1996-97 and 1997-98.

### 2.2 Field layout and Experimental details

The experimental area of wheat crop was divided into 20 plots of 5 m × 4 m size keeping a buffer of 1 m between two adjacent plots. Seed rate of wheat was 100 kg/ha. The seeds were sown at a row spacing of 20 cm and a plant spacing of 5 cm and the depth of sowing was 5 cm during all the three experiments.

### 2.3 Irrigation Treatments

The irrigation treatments consisted of irrigation scheduling based on maximum allowable depletion (MAD) of available soil water (ASW) criteria, which is given as

$T_1$ = 10% maximum allowable depletion (MAD) of available soil water (ASW)
$T_2$ = 30% MAD of ASW
$T_3$ = 45% MAD of ASW
$T_4$ = 60% MAD of ASW
$T_5$ = 75% MAD of ASW

### 2.3.1 Irrigation scheduling

Irrigation scheduling was based on the percentage depletion of available soil water in the root zone. The available soil water was taken as the difference between root zone water storage at field capacity and permanent wilting point. The maximum allowable depletion of the available soil water were fixed at 10, 30, 45, 60 and 75%. Using the data of soil moisture measured by Neutron probe and gravimetric measurements, the percentage depletion of available soil water in the effective root zone was estimated by the equation (Martin et al., 1990),

$$Depletion\ (\%) \quad = \quad 100 * \frac{1}{n} \sum_{1}^{n} \frac{FC_i - \theta_i}{FC_i - WP} \qquad ....(1)$$

where n is the number of sub-divisions of the effective rooting depth used in the soil moisture sampling, $FC_i$ is the soil moisture at field capacity for $i^{th}$ layer, $\theta_i$ is the soil moisture in $i^{th}$ layer and $WP$ is the soil moisture at permanent wilting point. The amount of water applied after the attainment of predefined *MAD* was calculated as:

$$V_d = \frac{MAD\ (\%) * (FC - WP) * R_z * A}{100} \qquad ...(2)$$

where $V_d$ is the volume of irrigation water, $R_z$ is the effective rooting depth and A is the surface area of the plot. The surface area of each plot was 20 m$^2$. Each 5m x 4m plot was made to small basins, which was furrowed and each furrow was fed individually. Measured amounts of water were applied to the furrows using a hosepipe and a water meters.

## 2.4 Data collection

For water balance and crop response to deficit irrigation, it was necessary to collect data on the weather parameter, profile soil moisture content and the growth attributes of the crop under consideration. These data were necessary in evaluating the effects of treatments on the final crop yield and for the estimation of water use efficiencies.

### 2.4.1 Weather Data

Daily values of weather parameter like solar radiation, maximum and minimum temperature, maximum and minimum relative humidity, wind speed and precipitation data for the experimental period were obtained from an automatic weather station installed near the experimental crop field.

### 2.4.2 Soil Profile Moisture Data

In order to assess the change in soil water status, soil moisture was measured in 0-15, 15-30, 30-45, 45-60, 60-90 and 90-120 cm soil profiles. The moisture content of topsoil layer (0-15 cm) was measured gravimetrically, whereas that of the lower layers was measured using the neutron probe. The access tubes installed for neutron probe were made of seamless aluminum alloy having 50 mm internal diameter. Moisture measurements were made on 2-3 days interval.

### 2.4.3 Crop Data

Crop parameters were measured during different stages of growth. The crop data included planting date, date of emergence, 20% cover date, full cover date, maturity date, harvest date, maximum rooting date, crop coefficient at full cover, planting depth and maximum root depth. The data on grain yield, above ground dry matter yield and leaf area index were recorded at different stages of crop growth during all the three crop experiments of wheat crop. The field water use efficiency, which is expressed as grain yield per unit cropped area per unit quantum of water applied to the field was computed for each treatment of each experiment for decision making purpose.

# III CERES- Wheat Growth Simulation Model

## 3.1. Model description

The cereal crop growth models were basically integrated into one program referred to as the GENERIC CERES model, and include barley, maize, millet, rice, sorghum and wheat. The wheat model is a stand-alone model known as CERES-wheat.

## 3.2 Input Files

Input files of CERES-Wheat models contain experimental details file, weather data file, soil data file and genotype data file.

### 3.2.1 Experimental Details File

The experimental file was developed to allow great flexibility in retrieving data needed to simulate various experiments from different locations and different years. The file contains the experiment code and name, the treatment combinations, and details of the experimental conditions (field characteristics, soil analysis data, initial soil water and inorganic nitrogen conditions, seedbed preparation and planting geometries, irrigation and water management, fertilizer management, organic residue applications, chemical applications, tillage operations, environmental modifications, harvest management), and simulation controls. The experiment code uses the same convention as the file naming system to provide information on institute, site, planting year, experiment number, and crop. The file can also contain the names of the people supplying the data set and information on the plot sizes etc., used in the experiment. It may also contain any incidents that occurred during the course of the experiment that may affect the interpretation of the data.

### 3.2.2 Weather Data File

Weather file contains all the available weather data. Daily weather data are required and must be available for the duration of the growing season, beginning with the day of planting and ending at crop maturity. Ideally, the weather file should contain data collected before planting to post-maturity. This would allow a simulation to be started before planting, thus providing an estimate of soil conditions at planting time. Weather data much prior to planting date would also allow users to select alternate planting dates, and simulate planting decisions based on weather and soil conditions. It is not necessary to have data for all variables, but the minimum data required for DSSAT v3.5 crop models are solar radiation, minimum and maximum air temperature and rainfall. The standard format for variables should be followed. In CERES-Wheat model, this file is independent of crop type.

### 3.2.3 Soil Data File

The soil file contains data on the soil profile properties. The file generally contains information that is available for the soil at a particular experimental site. This file contain soil identifier, information on soil texture and depth and the country, geographic data together with taxonomic information, information on soil properties that don't vary with depth, data on the first layer and so on. The number of layers in this file and the thickness of each layer must be consistent with the initial condition. The file may contain properties for several soils of the same classification, provided each soil has its own code number.

### 3.2.4 Genotype Data File

Genotype data file contains genetic coefficient data namely variety number and the genetic coefficient, which describe specific cultivar characteristics of wheat crop. Three files that are suggested for dealing with the morphological and physiological characteristics of a particular genotype are file for specific species (crop) characteristics, file for the "ecotype" characteristics within a species and file for the specific cultivar characteristics within an ecotype grouping. These files would contain all genotype specific inputs required for simulation. The use of at least one genotype file is highly recommended. For such a file, a standard format is recommended with each line beginning with a cultivar identification code.

## 3.3 Output Files

Output files contains the overview of input condition and crop performance, summery of soil characteristics and cultivar coefficient, crop and soil status at the main development stages, temporal distribution of simulated crop variables with time, simulated soil water with time, and selected harvest components and development duration for management strategy analysis. The output files are temporary information transfer files, created during simulation, and they are overwritten when a new simulation session is started.

## 3.4 Governing Equations in CERES-Wheat Model

The governing equations, which are used in CERES-Wheat model for wheat crop, are discussed under the following head.

### 3.4.1 Soil Water Balance

The soil water balance is calculated in CERES-Wheat models in order to evaluate the possible yield reduction caused by soil and plant water deficits. The model evaluates the
soil water balance of a cropped field or a fallow land using the following equation:

$$S = P + I - ET - R - D \qquad \ldots(3)$$

where,

$S$ = The quantity of resultant soil water
$P$ = Precipitation
$I$ = Irrigation
$ET$ = Evapotranspiration from soil and plants
$R$ = Runoff
$D$ = Drainage from the profile

Water content in any soil layer can decrease by soil evaporation, plant transpiration, root absorption or flow to an adjacent layer. The values of drained upper limit (field capacity) and drained lower limit (wilting point) are quite important in situations where the water supply is marginal. The values of field capacity and wilting point should be estimated in the field as the traditional laboratory measured wilting point and field capacity water contents have frequently proved inaccurate for establishing field limits of water availability.

### 3.4.2 Infiltration and Runoff

Infiltration of water into the soil is calculated as the difference between precipitation or irrigation and runoff. Runoff is calculated using USDA-SCS procedure but with a small modification. The SCS technique considers the wetness of the soil, calculated from the previous rainfall amount, as an additional variable in determining runoff amount. The modified technique for layered soils replaces the wetness of the soil in the layers near the surface for the antecedent rainfall condition.

### 3.4.3 Drainage

Since the plants can take up water while drainage is occurring, therefore, the drained upper limit soil water content is not always the appropriate limit of soil water availability. Many productive agriculture soils drain quite slowly and may thus provide an appreciable quantity of water to plants before drainage practically stops. In DSSAT v3.5, drainage rates are calculated using an empirical relation that evaluates field drainage reasonably well.

The drainage formula assumes fixed saturated volumetric water content, $\theta_0$ and fixed upper limit water content, $\theta_u$. Thus drainage takes place when the water content, $\theta_t$, at any time, t, lies between $\theta_0$ and $\theta_u$. The equation used is:

$$\theta_t = (\theta_0 - \theta_u)\exp(-K_d\, t) + \theta_u \qquad ..(4a)$$

where,

$\theta_t$ = Water content, at any time, t

$\theta_0$ = Saturated volumetric water content

$\theta_u$ = Upper limit water content

$K_d$ = Fraction of excess water drained per day

$t$ = time

The value of $K_d$ is assumed to be constant for the whole soil profile because, in many soils, the most limiting layer to water flow dominates the drainage rate from all parts of the soil profile. A problem with Eqn. 4a for drainage evaluation in the field is that soils seldom reach saturation and it becomes difficult to determine an initial value for *t*. Ritchie (1985) presented a method for drainage of water above the drained upper limit, $\theta_u(L)$. The method was modified to account for restricting layers within the soil profile. The original soil water model assumed that water in excess of $\theta_u(L)$ would drain out of the profile at an exponential rate defined by:

$$\frac{d\theta_t(L)}{dt} = -K_d\,(\theta_t(L) - \theta_u(L))\exp\,(\text{-K}_\text{d}\,\text{t}) \qquad ...(4b)$$

where,

$\theta_u(L) =$ Volumetric water content in layer *L*

$\theta_t(L) =$ Volumetric water content at time t in layer *L*

Thus, drainage $D_t$, is computed by

$$D_t = \sum_{i=1}^{N} -K_d \left(\theta_t(L) - \theta_u(L)\right) z(L) \qquad \ldots(4c)$$

where,

$N$ = number of soil layers

$z\ (L)$ = depth of layer, mm

In the model constant drainage throughout a day is assumed and the value of $K_d$ represents the fraction of water between $\theta_u$ and $\theta_t$ that drains in one day. For Eqn 4c to be used, $\theta_t$ must be greater than $\theta_u$. The value of $\theta_t$ at any depth is updated daily to account for any infiltration, water flow or root absorption.

### 3.4.4 Root Water Absorption

The model calculates root water absorption using an approach in which the soil or root resistance determines the flow rate of water into roots. The soil limited water absorption rate, $q_r$ considers radial flow to single roots and is expressed as:

$$q_r = \frac{4\pi K(\theta)\,(\psi_r - \psi_s)}{\ln(c^2 / r^2)} \qquad \ldots(5a)$$

where,

$q_r$ = soil limited root water absorption rate, mm$^3$ water/mm of root/d

$K(\theta)$ = soil hydraulic conductivity, mm/d

$\psi_r$ = water potential at the root surface, mm

$\psi_s$ = bulk soil water potential, mm

$r$ = root radius, mm

$c$ = radius of the cylinder of the soil through which water is moving, mm

The hydraulic conductivity $K(\theta)$ is approximated based on the assumption that all soils have a constant conductivity of 5*10$^{-5}$ mm/d at the lower limit of water available to the plant, $\theta_{LL}$. The relationship used is:

$$K(\theta) = 5 * 10^{-5} \exp\left[C_T\left(\theta_t - \theta_{LL}\right)\right] \qquad \ldots(5b)$$

where, $C_T$ is texture dependent coefficient that is approximated from $\theta_{LL}$ and can be expressed as:

$$C_T = 100\left(1.2 - 2.5\theta_{LL}\right) \qquad \ldots(5c)$$

The sum of the maximum root absorption from each soil depth gives the maximum possible uptake from the profile. If the maximum uptake exceeds the maximum calculated transpiration rate, the maximum root water absorption rates calculated for each depth are reduced proportionally so that the uptake becomes equal to transpiration rate. If the maximum uptake is less than the maximum transpiration, transpiration rate is set equal to the maximum absorption rate.

### 3.4.5 Dry Matter Production

In CERES-wheat models the potential dry matter production is a linear function of intercepted photo synthetically active radiation (PAR). The percentage of incoming PAR intercepted by the canopy is an exponential function of leaf area index (LAI).

The actual rate of dry matter production is usually less than the potential rate due to the effects of non-optimal temperature or water stress. A weighted daytime temperature is calculated from the minimum and maximum temperature for the use in biomass evaluation.

The optimum daytime temperature is considered as 18°C to 20°C. Water stress reduces dry matter production rates below the potential whenever crop extraction of soil water falls below the potential transpiration rate calculated for the crop.

### 3.4.6 Leaf Area Index

Plant leaf area has an important influence on light interception and dry matter production. The rate of leaf area expansion is a component of plant growth that is quite sensitive to environmental stresses. For example, leaf growth is more sensitive to plant water deficits than photosynthesis. Cool temperature or moderate drought stresses reduce the expansion growth more than photosynthesis, causing increase in specific leaf weight and increasing the proportion of assimilate partitioned to the roots.

CERES-Wheat model accounts for these plant responses by using separate relationships to calculate the influence of temperatures water deficits on photosynthesis and leaf growth.

## IV Results and Discussions

The results of the field experiments are presented in this section. It includes the calibration and validation results of CERES-Wheat model. A critical discussion of the results leading to management of irrigation water for wheat crop is also presented.

## 4.1 Crop Response

Measurements of grain yield, above ground dry matter and leaf area index were made in all the three crop experiments of wheat crop conducted during 1995-96 through 1997-98 crop seasons

### 4.1.1 Grain Yield

The irrigation schedules were based on 15%($T_1$), 30% ($T_2$), 45% ($T_3$), 60% ($T_4$) and 75% ($T_5$) maximum allowable depletion (MAD) of available soil water (ASW). The grain yield was found to be almost similar for $T_1$, $T_2$ and $T_3$ during all three-crop experiments of wheat crop (Fig 1). The grain yield was low for T4 and T5 treatments because soil moisture was depleted sufficient enough to retard the extraction of water by root and thereby affecting the grain formation. Similar trends were also observed during all the three crop seasons of wheat crop.

### 4.1.2 Above Ground Dry Matter

Above ground dry matter also followed a similar trend as that of grain yield (Fig.2). It was observed that, when the irrigation was scheduled at a depletion level of less than or equal to 45% MAD, there was no significant change in the plant above ground dry matter yield. However, a reduction in the above ground dry matter yield was noticed when the irrigation was scheduled at 60% to 75% MAD because soil moisture was depleted sufficiently and affected the root water extraction. Similar trend was observed during all the three experiments for wheat crop.

### 4.1.3 Leaf Area Index

Leaf area index also followed similar trend as that of grain yield (Fig.3). It was observed that, when the irrigation was scheduled at a depletion level of less than or equal to 45% MAD, there was not much change in the leaf area index. However, a reduction in the leaf area index was noticed when the irrigation was scheduled at 60% to 75% MAD due to considerable depletion of soil water affecting the root water extraction. This trend was observed during all the three experiments

## 4.2 Water Use Efficiency

The water use efficiency is usually expressed in two ways: (a) crop water use efficiency and (b) field water use efficiency. Field water use efficiency was considered in this study. The field water use efficiency was estimated in terms of grain yield obtained per unit of land used and per unit of water available to the field. The field water use efficiency was computed for experiment 1 through 3 to determine how effectively the irrigation water was used by the crop. The results are presented in Fig.5.

### 4.2.1 Field Water Use Efficiency

Under treatment $T_1$ the irrigations events were scheduled at small intervals. The quantum of water applied during each irrigation events was low for this treatment. The irrigation interval and quantum of water applied during each irrigation increased for treatments $T_2$, $T_3$, $T_4$ and $T_5$ in that order. This trend was similar during all the crop experiments.

The field water use efficiency was taken as the ratio of the grain yield and total field water used (precipitation + irrigation) per unit area during the crop experiments. The results shown in Fig. 5 revealed that the highest field water use efficiency was attained when the irrigation was scheduled at 45% depletion of ASW ($T_3$). A rising trend of field water use efficiency was noticed from $T_1$ to $T_3$ after that it decreased for $T_4$ and $T_5$ as the irrigations were delayed. This trend was obtained during all the crop seasons.

From the results of field experiments conducted over a period of three seasons it could be inferred that irrigation schedule with 45% maximum allowable depletion of available soil water should be maintained during the non-critical stages to obtain high values of yield parameters and field water use efficiency.

## 4.3 Performance of CERES-Wheat Model

### 4.3.1 Calibration

The model was calibrated using the experimental data on grain yield, above ground dry matter and maximum leaf area index. The well-watered treatment (10% MAD or $T_1$) of each experiment was selected for calibration. The file containing genetic coefficients was used to estimate the genetic coefficient values. Model calibration was performed for each experiment separately and an average value of each genetic coefficient was considered for further use. The best set of genetic coefficients was obtained by the best-fit method. All the genetic coefficients have a pre-assigned range and calibrated values should generally fall within that range.

A fairly good agreement was found between simulated and measured grain yield of wheat crop. It was also found that the simulated and measured above ground dry matter and leaf area index was matching reasonably well.

### 4.3.2 Validation

After getting a good match between the predicted and observed values of crop parameters for the well-watered treatment (10% MAD or $T_1$), through calibration, the model was validated for other four treatments of irrigated crops i.e. 30%, 45%, 60% and 75% depletion of available soil moisture (ASM). The genetic coefficients determined by the process of calibration were used for validation. For validation, the model was run independently for $T_2$, $T_3$, $T_4$ and $T_5$ treatments of each experiment. The results of simulations of crop growth parameters for all experiments of wheat crop are discussed separately (Fig. 1 to 3)

#### 4.3.2.1 Simulation of grain Yield

Comparison of the simulated and measured grain yield at harvest for all experiments of wheat crop under different treatments is presented in Fig.1. The simulated dry yield for $T_1$, $T_2$ and $T_3$ were more or less the same in case of a particular experiment. This is because the plants were not under any soil water stress particularly under these treatments. The grain yield reduced during $T_4$ and $T_5$ because the plants experienced some stress during their growth cycle. A similar trend was observed during all the three experiments. A reasonably good agreement (Fig.4a) was found between simulated and measured values of grain yield of wheat crop during all experiments. The regression analysis gave a coefficient of determination ($R^2$) value of wheat crop of 0.96 (Fig 4a).

#### 4.3.2.2 Simulation of above ground dry matter

The simulated above ground dry matter yield was found to be in good agreement with the measured above ground dry matter. Comparison of the simulated and measured above ground dry matter at harvest for all experiments under different treatments is presented in Fig. 2. In general, a good agreement (Fig. 4b) was found between simulated and measured values of above ground dry matter during all experiments except the second experiment where the model over estimated ADM for the treatments T4 and T5. The regression analysis gave a $R^2$ value of wheat crop of 0.94 (Fig 4b).

#### 4.3.2.3 Simulation of Leaf Area Index

Comparisons of the simulated maximum and measured maximum leaf area index for all experiments of wheat crop under different treatments are presented in Fig. 3. In general, a very good agreement (Fig. 4c) was found between simulated and measured values of leaf area index during all experiments of wheat crop. The regression analysis gave a $R^2$ value of wheat crop of 0.91 (Fig 4c).

## 4.4 Soil Water Balance

The soil moisture for 15-120 cm soil profile was determined by using a neutron probe, while the soil moisture for 0-15 cm soil profile was determined by conventional gravimetric method**.**

### 4.4.1 Depth and Time Variation of Soil Moisture

The temporal variations of soil moisture in the root zone and below the root zone of the experimental wheat crop are presented in Fig. 6 through 10. The figures reveal that the soil moisture experienced a cyclic temporal variation in all the layers. This trend was observed irrespective of the level of irrigation (MAD level). The amplitude of this cyclic variation was higher in upper layers than in lower layers.

A comparison of the three experiments in terms of the temporal variation of soil moisture in the experimental wheat crop plots at 10% maximum allowable depletion (MAD) of available soil water (ASW) are presented in Fig. 6a through 6c. In experiment 1, there was a rapid decline of soil moisture (Fig. 6a) in 0-15 cm soil profile with effect from 76 days after sowing (DAS) to the end of growth period. The lower layers of 15-30, 30-45 and 45-60 cm soil profiles also exhibited a gradual decline with effect from 76 DAS up to the end of the growth period. The rate of decline was lower towards the lower layers. The 60-90 cm soil profile was not affected at this level of depletion. In experiment 2 also, the rate of depletion was more prominent with effect from 76 DAS (Fig.6b) than the earlier periods at all soil depths. A similar trend was found in experiment 3 for $T_1$. The rise in the moisture content in 0-15 cm soil profile (Fig. 6a) above the field capacity on 16 DAS and 62 DAS were due to the occurrence of rainfall. This resulted in excess storage of water in the uppermost soil profile (0-15 cm) as well as in the crop root zone. The crop was irrigated at an interval of 3-4 days under this irrigation schedule. Since the irrigation water application was frequent under this irrigation schedule, the amplitude of cyclic variation and the time span of irrigation event was low.

Soil moisture in 0-15, 15-30, 30-45 and 45-60 cm soil profiles at 30% MAD ($T_2$) also exhibited cyclic pattern. The results are presented in Fig. 7a through 7c. The results revealed that the soil water was extracted from all the layers of the root zone but most of the extraction was from 0-15, 15-30, and 30-45 cm soil profiles. Since the irrigation was scheduled at 30% depletion, the plants extracted water to meet the evapotranspiration demand of the crop. The soil moisture in 0-15 cm soil profile was seen to rise above the field capacity a few times during each experiment due to rainfall events. A continuous sharp decline of soil moisture in all soil profiles were observed with effect from 82 DAS in experiments 1 except 92 DAS in 0-15 cm soil profile (Fig. 7a) and 90 DAS in experiment 2 (Fig. 7b); 92 DAS in experiment 3 (Fig. 7c). During experiment 3, a peak (Fig. 7c) was observed on 72 DAS because of the rainfall immediately after irrigation. The schedule T2 being a dryer regime than T1, the magnitude of cyclic variation was higher in 30-45 and 45-60 cm soil profiles as compared to similar layers of $T_1$ during all the crop seasons. The frequency of irrigation was lower under this irrigation schedule than that of $T_1$, and thereby, the time span of cyclic variation was higher than that of $T_1$.

The variations of soil moisture with depth under 45% MAD ($T_3$) is presented in Fig. 8a through 8c. High amplitude of cyclic variation was noted in all soil profiles of the root zone. Since the irrigation were scheduled at 45% MAD, the time span of variation was also higher in this irrigation schedule compared to $T_1$ and $T_2$. The plant roots penetrated deeper in search of water as it was not adequate in the upper soil layers. A continuously decreasing trend was observed with effect from 66 DAS in 30-45 and 45-60 cm soil profile (Fig. 8a). This is because the roots of the plants were developed by this time and they extracted the water from these lower layers also in addition to 0-15 and 15-30 cm soil profile. During experiment 2 (Fig. 8b), the soil water was also contributed from 30-45 and 45-60 cm soil profiles with effect from 72 DAS because of the developed root system. The temporal variation of soil water was observed to be similar during all experiments. The temporal variation under $T_3$ exhibited cyclic pattern in 0-15 and 15-30 cm soil profiles during experiment 1 (Fig. 8a), while 30-45, 45-60 and 60-90 cm soil profiles showed a gradual decline after 90 DAS (Fig. 8a). A similar trend was observed during experiments 2 (Fig. 8b), and 3 (Fig. 8c).

Considerable soil moisture fluctuation was observed under 60% MAD ($T_4$) schedule. All soil profiles exhibited discernible cyclic variation (Fig. 9a through 9c), with considerably low amplitudes in the lower layers as compared to those observed at upper layers. It is revealed from Fig. 9a through 9c that the time span of cyclic variation is more compared to that of $T_1$, $T_2$ and $T_3$. This was ascribed to the large volume of water applied during each irrigation event under this schedule. The contribution of soil water, to the plant roots, can be seen from all the profiles of the root zone (Fig 9a). The soil water was contributed from all soil profiles during experiment 2 (Fig. 9b) also. During this experiment a light precipitation raised the profile soil water content with effect from 56 DAS. The increasing trend of soil water in all soil profiles due to this precipitation is revealed from Fig. 9a and 9b. However, the rate of increase of profile soil water content was lower towards lower soil profiles. The soil profile (60-90 cm) below the root zone remained unaffected due to this precipitation. During experiment 3, the occurrence of precipitation on 74 DAS filled the uppermost soil profile. However, the amount of water received by 15-30, 30-45 and 45-60 cm soil profiles was low (Fig. 9c).

The variations of soil moisture with depth under 75% MAD ($T_5$) for all the crop seasons is presented in Fig. 10a through 10c. Considerable soil moisture fluctuation was observed under this irrigation schedule. The 0-15 and 15-30 cm soil profiles exhibited higher cyclic variation as compared to 30-45 and 45-60 cm soil profiles. The time span of cyclic variation was higher than that of the other treatments, when 75% depletion of available soil water was imposed with effect from 27 DAS (Fig. 10a). The rate of decrease of soil water depletion was faster at the beginning (28 DAS through 50 DAS and 60 DAS through 80 DAS) of the treatment. The water was lost through uppermost soil profile at a faster rate because of the evaporation from soil surface and transpiration from the grown up plants. Since the roots were developed enough, one month after sowing, the soil water was extracted from 30-45 and 45-60 cm soil profiles also (Fig. 10a). However, the magnitude of contribution from these two soil profiles was low as compared to 0-15 and 15-30 cm soil profiles. The time span of cyclic variation was found to be higher during $T_5$ as compared to other treatments. A similar cyclic variation was observed during experiments 2 (Fig. 10b), 3 (Fig. 10c). Initially the crop water extraction from the lower layers was not significant because no stress was maintained during the initial stages of crop growth. The depth variation of moisture within 60 cm soil profile was greatly influenced by the increasing crop water extraction at later growth periods as shown in Fig. 10a through 10c.

As observed from all three experiments, the 60-90 cm soil profile during irrigation schedules $T_1$, $T_2$, $T_3$, $T_4$ and $T_5$ (Fig. 6a through 10c) tended to remain almost steady upto the last irrigation event. However, when irrigation were scheduled at $T_5$, the soil profile below the root zone also tended to decline with effect from 90 DAS during experiment 1 (Fig. 10a), 86 DAS during experiment 2 (Fig. 10b) and 88 DAS during experiment 3 (Fig. 10c). Since the irrigation was scheduled at 75% depletion of ASW in this schedule, plants extracted enough water from the root zone soil profile, besides that soil water was also contributed through capillary rise from a profile below the root zone. Soil moisture below the root zone (60-90 cm soil profile) of the experimental plots experienced minimum cyclic variation with time. In general a slight continuous decline was observed when irrigations were discontinued. This trend was observed during all three experiments. It was observed that the plants extracted most of the soil moisture from 0-45 cm soil profiles in case of wheat crop. Therefore, it is inferred that only 0-45 cm of soil profile should be considered for scheduling of irrigation for wheat crop grown in sandy loam soil in the sub-tropical regions.

### 4.4.2 Temporal Variation of Profile Soil Water Storage

The depletion pattern of measured and CERES- wheat model simulated soil water storage for the soil layers 0-15, 15-30, 30-45, 45-60 and 60-90cm for irrigation schedule based on 10%MAD of ASW of experiment 1 are presented in Fig. 11. It is observed from Fig.11 that immediately after irrigation, the quantum of water added in the RZWS was higher in 0-15 cm soil profile than the other layers during experiment 1. The maximum and minimum RZWS within the irrigation cycles fluctuated between 17%VMC and 9%VMC. The amplitude of the cyclic variation was more in 0-15 cm soil profile mainly due to the evaporation from the soil surface. As expected, the difference between maximum and minimum RZWS within the irrigation cycle was lower in 15-30 cm soil profile as compared to 0-15 cm soil profile (Fig. 11). The RZWS ranged between 16.5%VMC and 12.5%VMC in this soil profile. A decline in RZWS was noted in this soil profile after the withdrawal of the irrigation 80 DAS. The range of cyclic variation was noted to be between 16%VMC and 13%VMC in 30-45 cm soil profile (Fig.11). Not much cyclic variation was observed in this soil profile. A decline of soil moisture was observed 80 DAS. However, the rate of decline was lower as compared to 0-15 and 30-45 cm soil profile The trend as seen in Fig. 11, implied that the plants did not extract much moisture from 45-60 cm soil profile as the soil moisture varied only between 16% VMC and 14% VMC. A decline in soil moisture in this layer was also observed after withdrawal of irrigations. However, the decline rate from 45-60 cm soil profile was lower than the upper layers. The cyclic variation of RZWS was found to be negligible (16%VMC and 15%VMC) in 60-90 cm soil profile (Fig. 11). When irrigations were withdrawn, a slight decrease in soil moisture storage was noted in this layer. The change in soil water storage below the root zone stems from both the downward flux due to drainage and upward flux due to capillary rise induced by evaporation.

The profile soil moisture content was also simulated using the CERES- Wheat model for wheat crop. A very good agreement was noted between measured and simulated profile soil moisture content for each soil profile for all the treatment during all the three experiments. The regression analysis gave a coefficient of determination ($R^2$) value for measured and simulated profile soil moisture content for 0-15, 15-30, 30-45, 45-60 and 60-90 cm soil profile of wheat crop of 0.91, 0.89, 0.88, 0.80 and 0.73 respectively (Fig 12).

## V. Conclusions

1. Under water scarcity condition, when soil water stress is imposed during non-critical stages of growth, irrigation is to be scheduled at 45% maximum allowable depletion of available soil water for wheat crop grown in sandy loam soils in sub-humid regions in order to obtain maximum grain yield and above ground dry matter.
2. In order to obtain the highest water use efficiency (WUE), irrigation is to be scheduled at 45% maximum allowable depletion of available soil water for wheat crop in sandy loam soil.
3. CERES-Wheat model simulates the profile soil moisture content both under dry and wet regimes with considerable accuracy.
4. CERES-Wheat model can successfully be used for simulation of yield, above ground dry matter and maximum leaf area index of wheat crop in sub- humid sub-tropical climatic regions.
5. The plants extracted most of the soil moisture from 0-45 cm soil profile in case of wheat crop. Therefore, only 0-45 cm of soil profile is to be considered for scheduling of irrigation water for wheat crop grown in sandy loam soils in the sub-tropical regions and under water scarcity conditions.

(a)

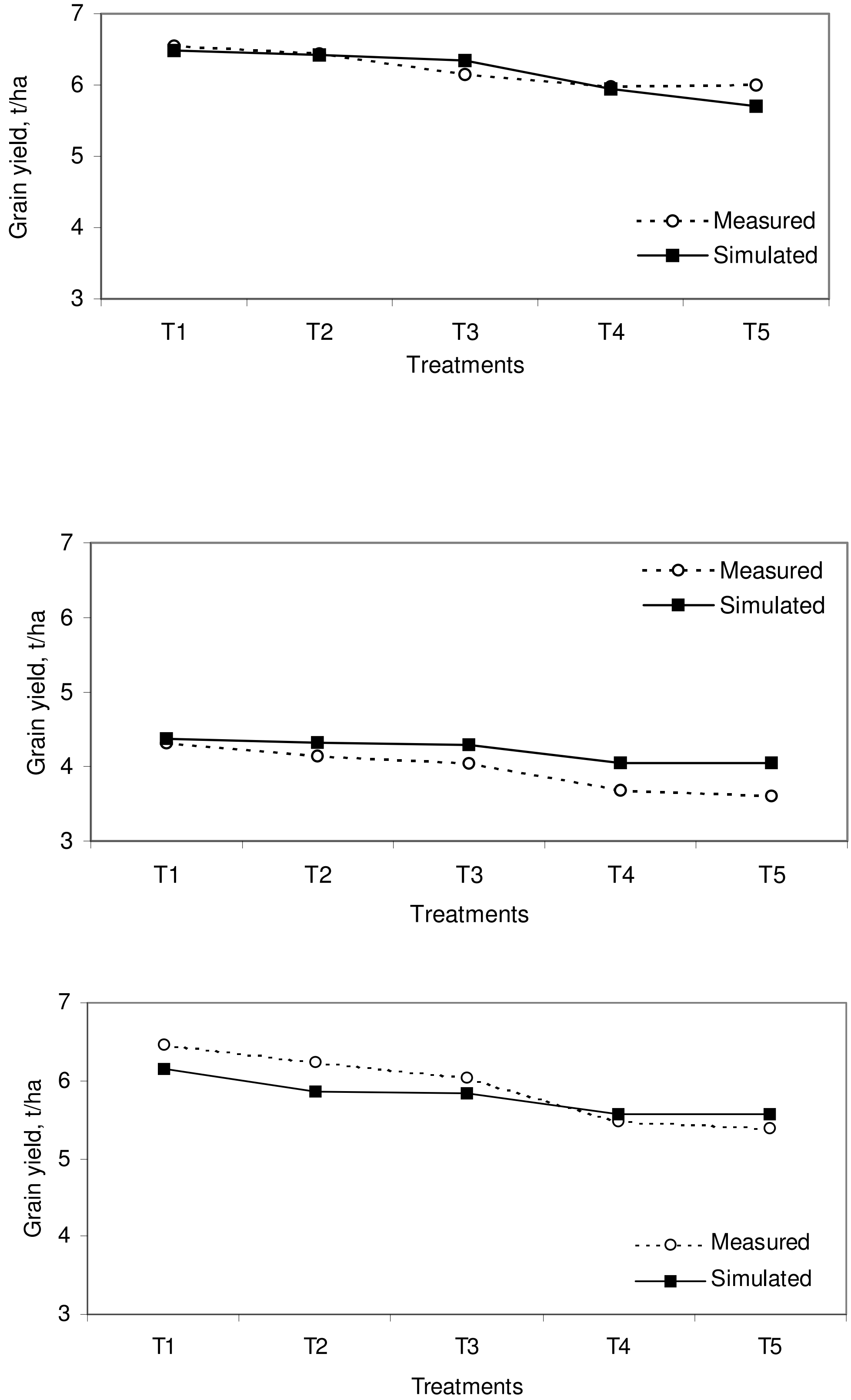



Fig.1. Measured and Simulated grain yield of wheat crop under different scheduling of irrigation during (a) experiment 1, (b) experiment 2 and (c) experiment 3

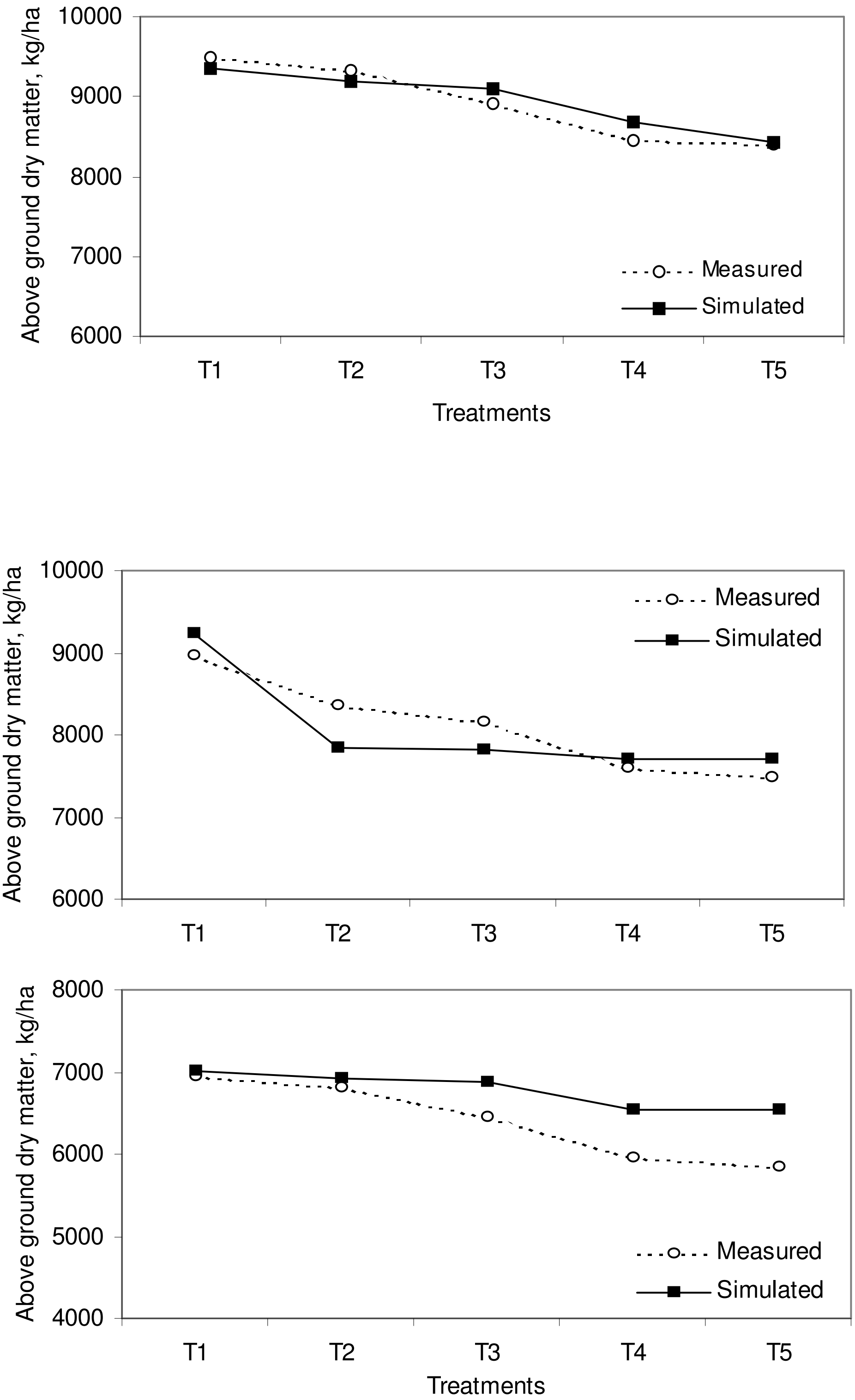



Fig.2. Measured and Simulated above ground dry matter of wheat crop under different scheduling of irrigation during (a) experiment 1, (b) experiment 2 and (c) experiment 3.

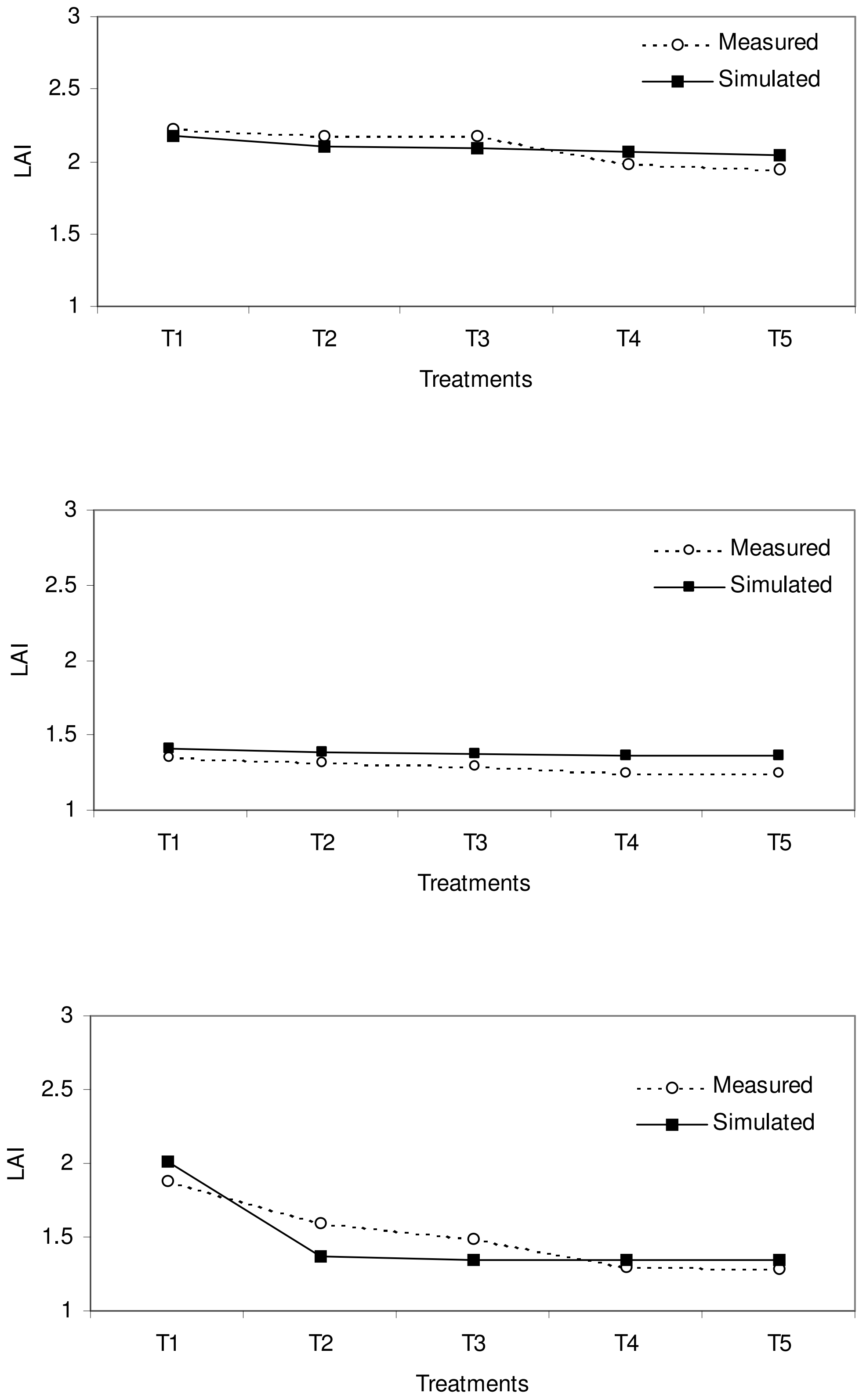



Fig 3. Measured and Simulated grain yield of wheat crop under different scheduling of irrigation during (a) experiment 1, (b) experiment 2 and (c) experiment 3.

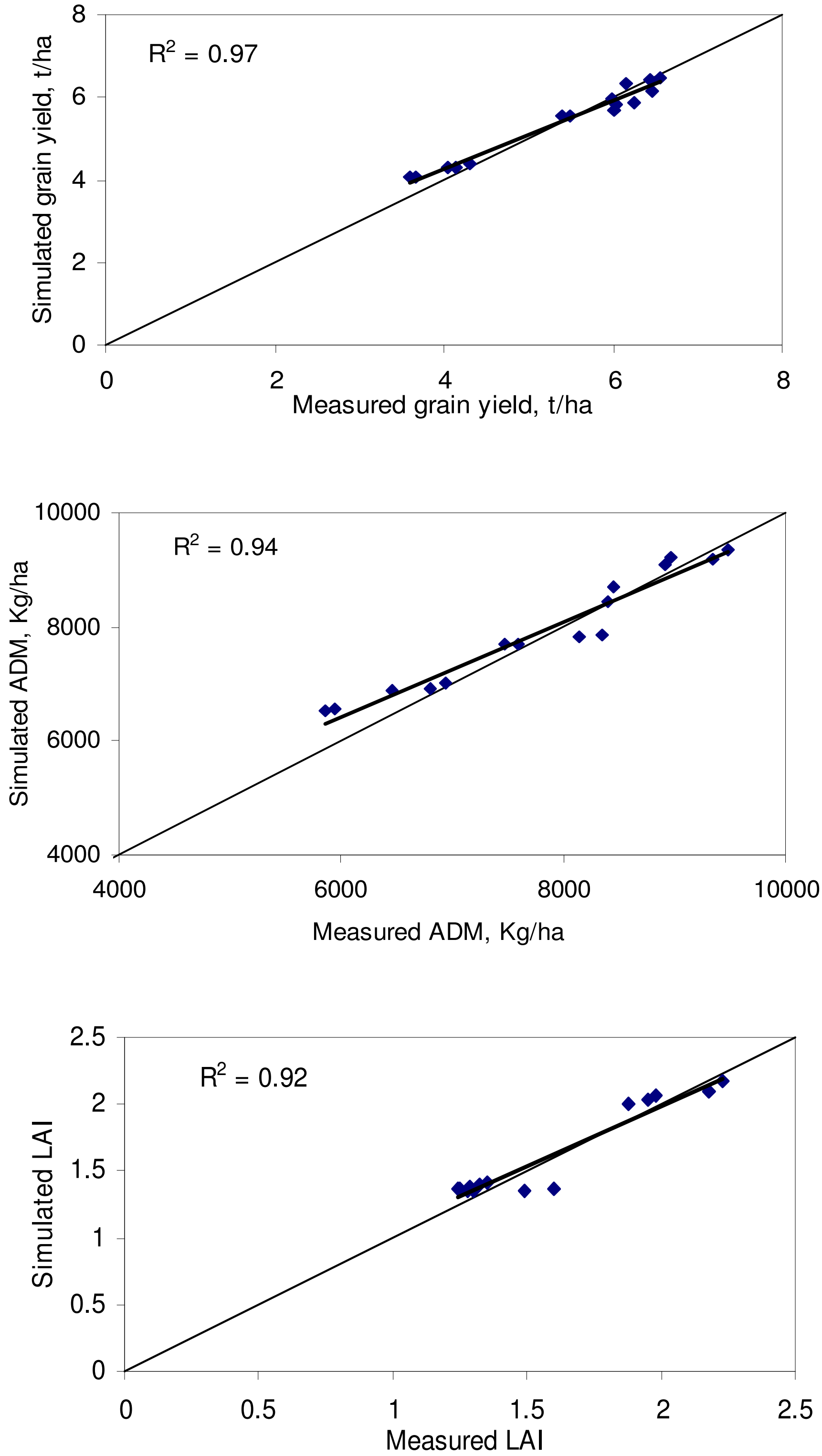



Fig. 4 Comparison of simulated and measured results of (a) grain yield (b) above ground dry matter (ADM) (c) LAI of wheat crop under different scheduling of irrigation during experiments 1 through 3.

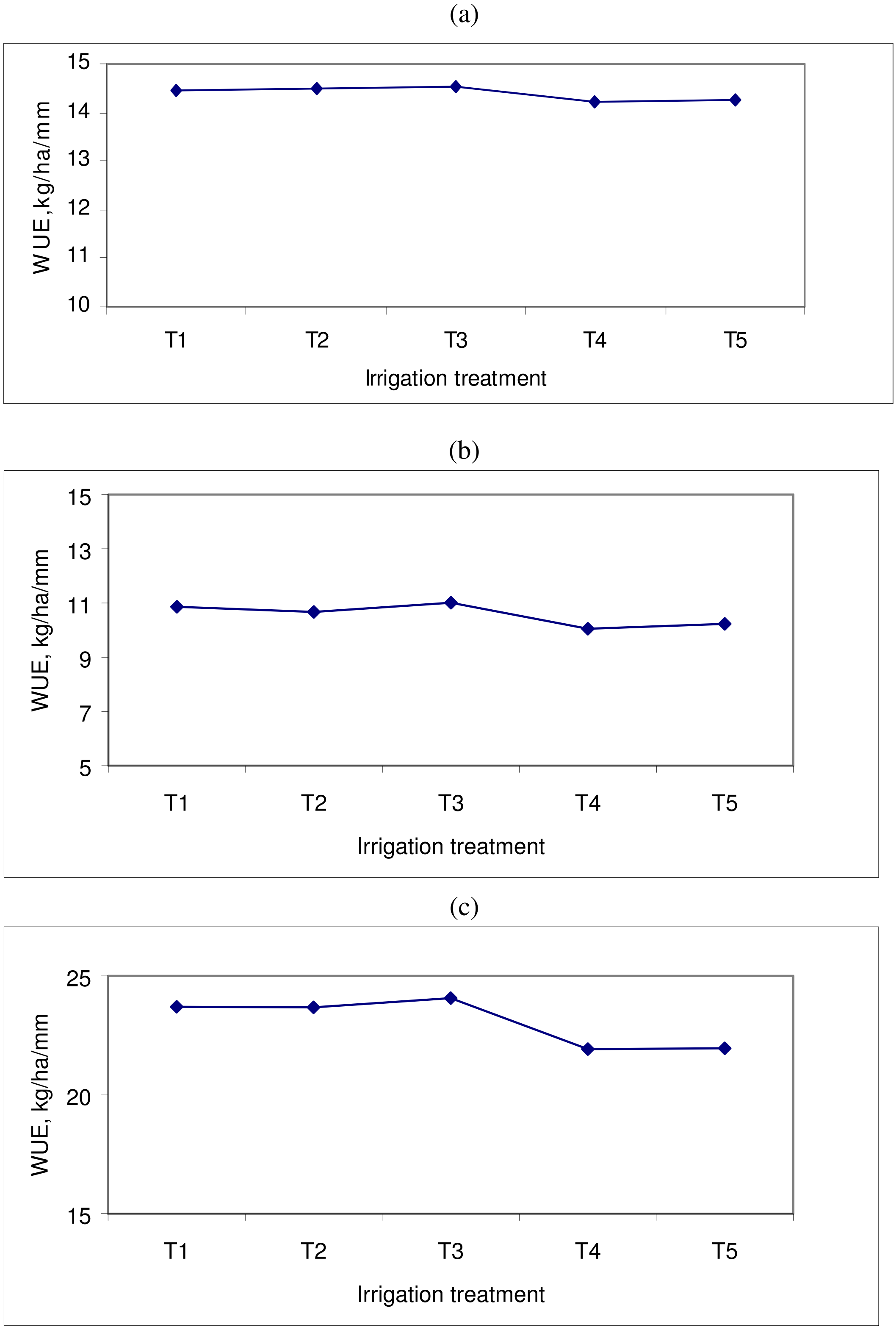



Fig 5. Field water use efficiency of wheat crop under different scheduling of irrigation during: (a) experiment 1 (b) experiment 2 (c) experiment 3

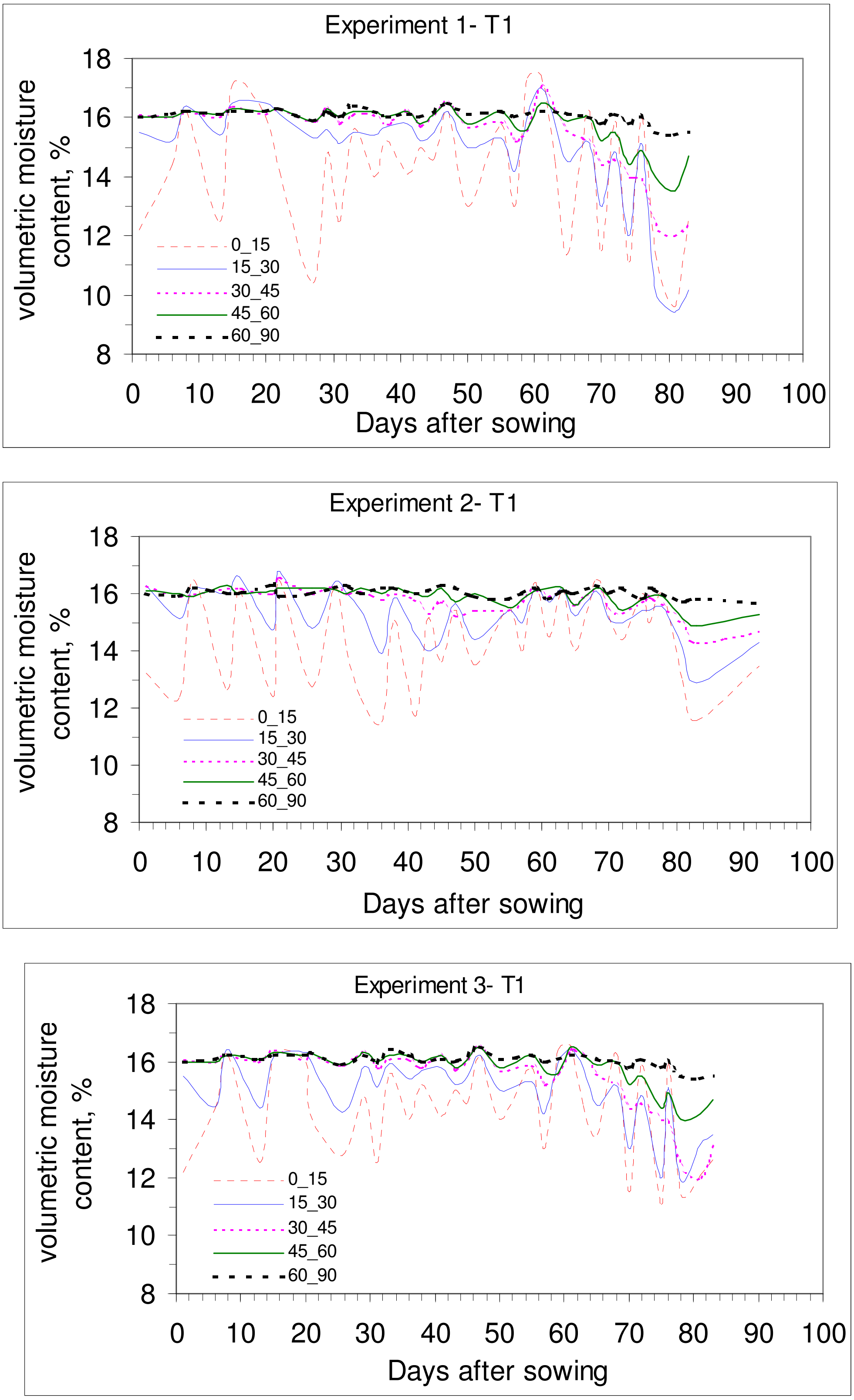



Fig 6. Temporal variation of soil moisture in wheat crop root zone at 10% MAD of available soil water ($T_1$) during (a) experiment 1 (b) experiment 2 (c) experiment 3.

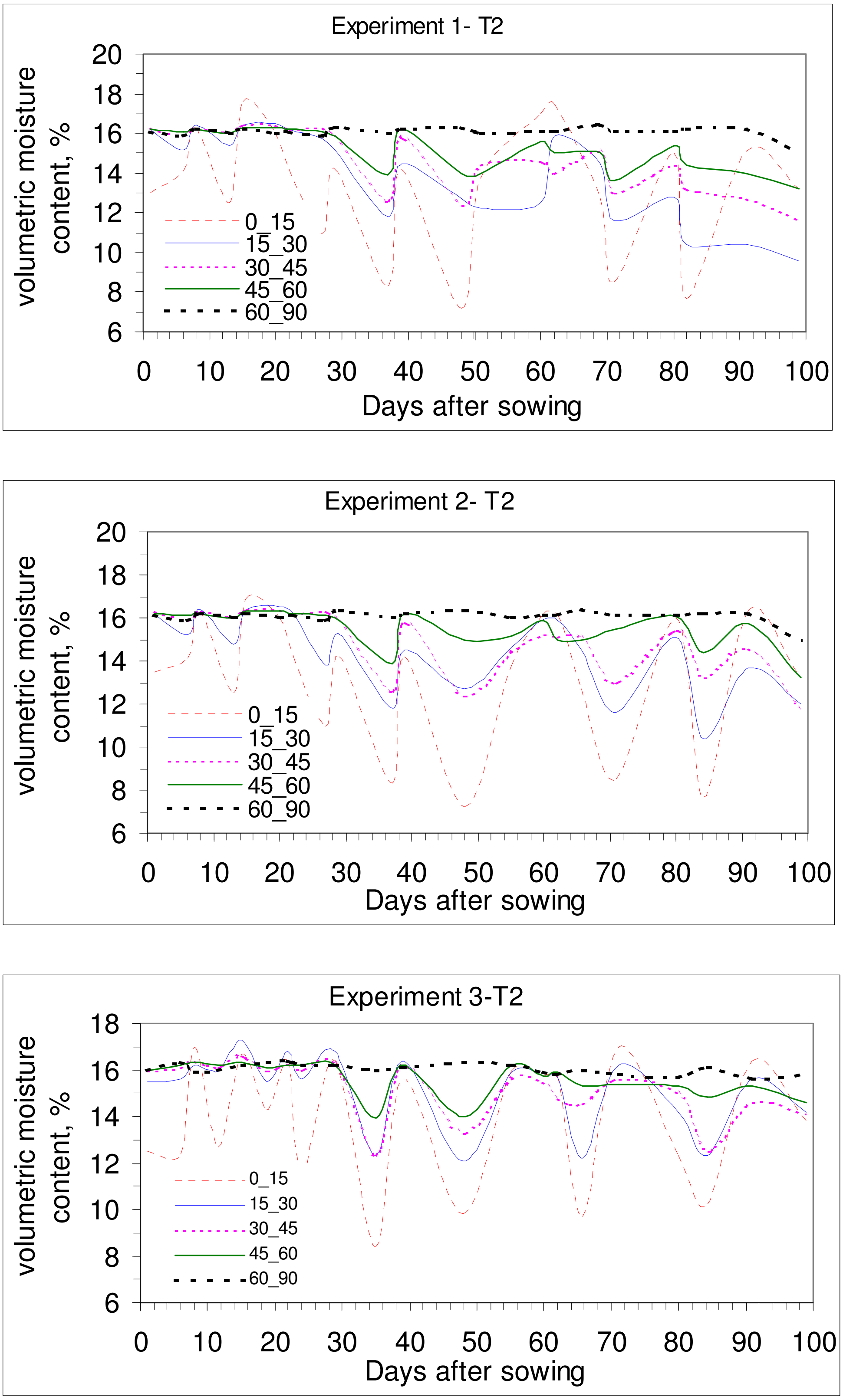



Fig 7. Temporal variation of soil moisture in wheat crop root zone at 30% MAD of available soil water ($T_2$) during (a) experiment 1 (b) experiment 2 (c) experiment 3.

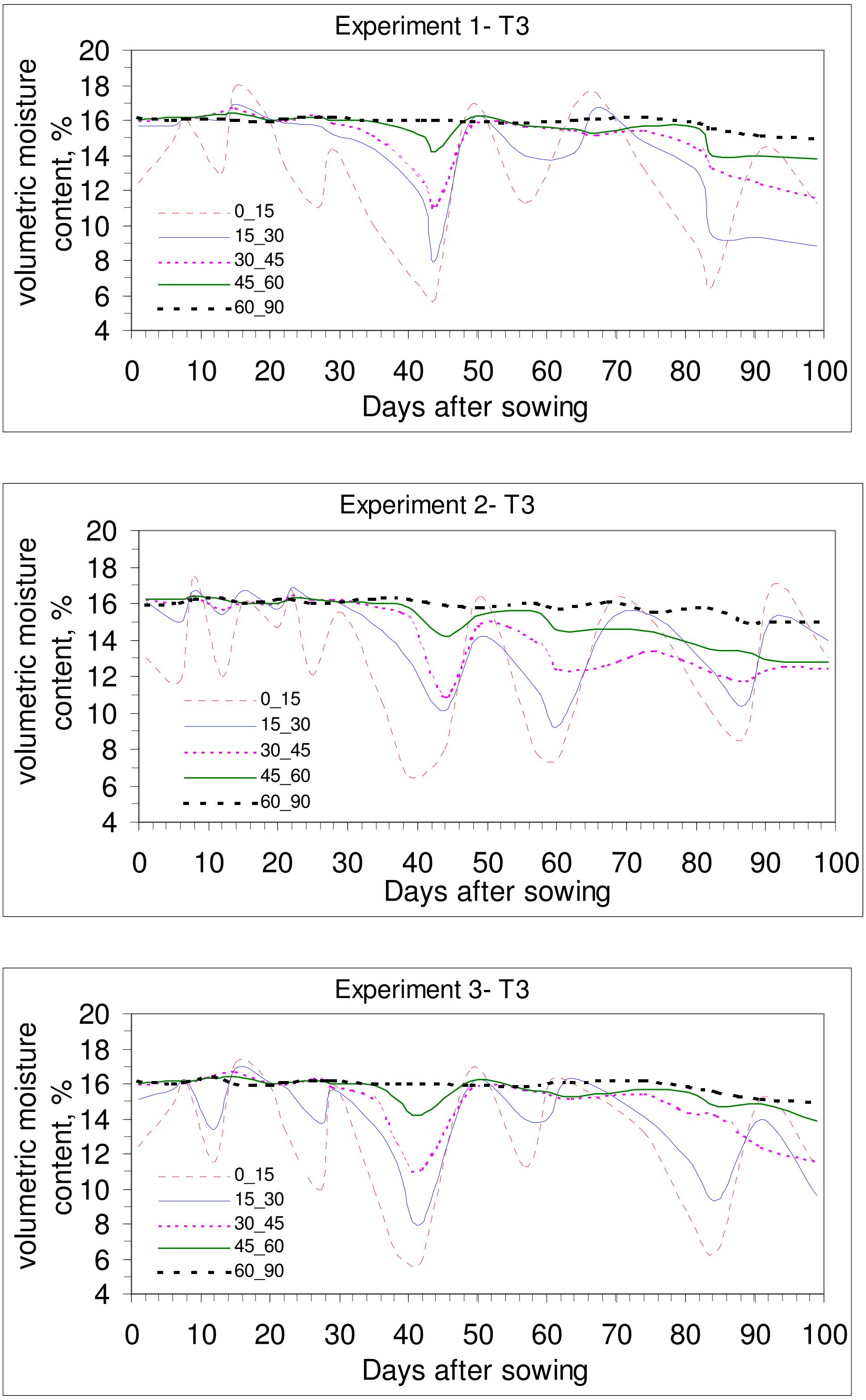



Fig 8. Temporal variation of soil moisture in wheat crop root zone at 45% MAD of available soil water ($T_3$) during (a) experiment 1 (b) experiment 2 (c) experiment 3.

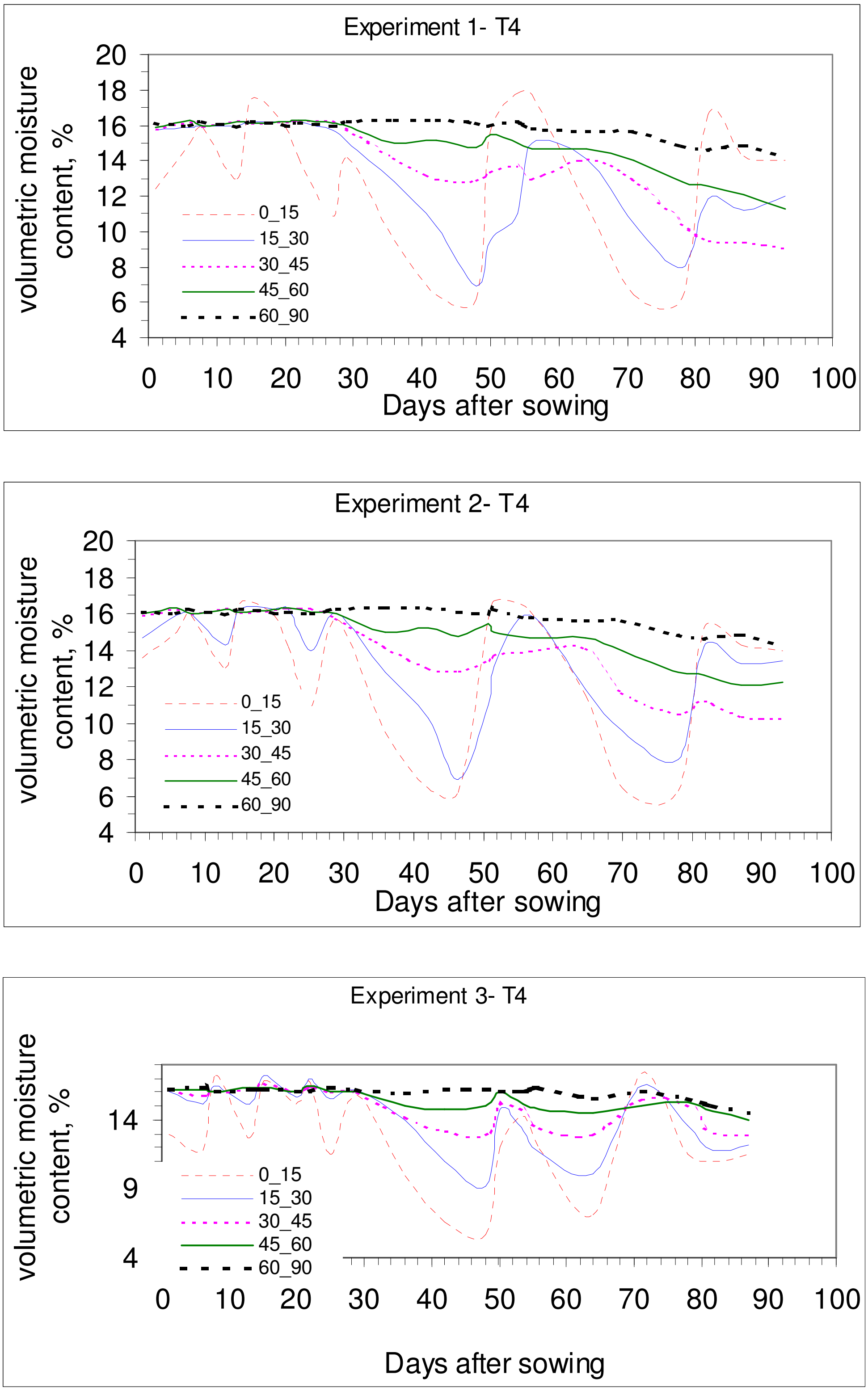
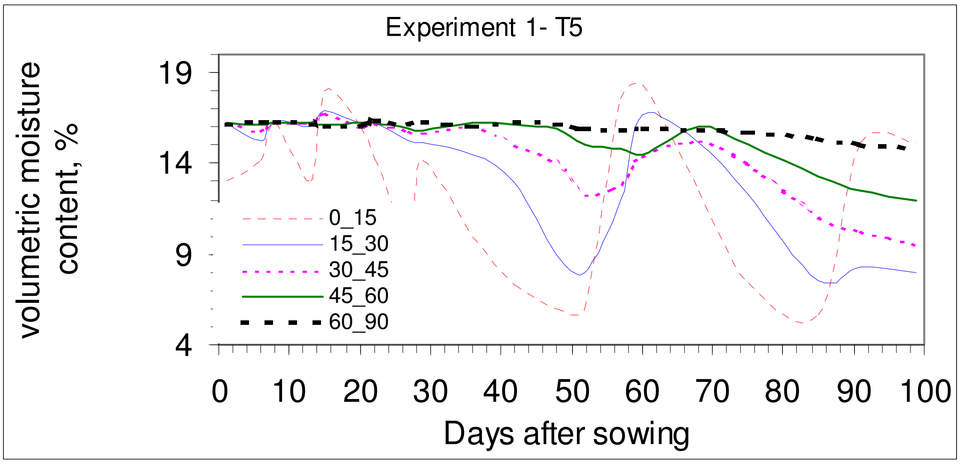
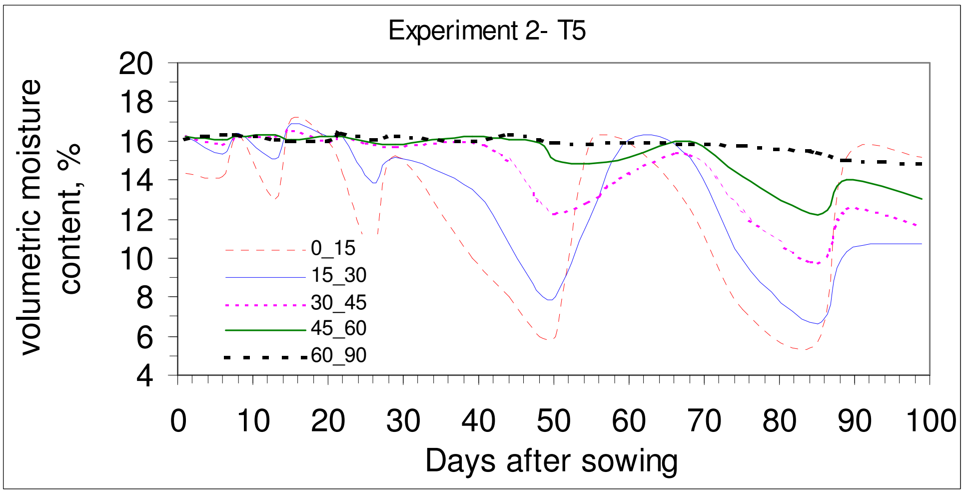



Fig 9. Temporal variation of soil moisture in wheat crop root zone at 60% MAD of available soil water ($T_4$) during (a) experiment 1 (b) experiment 2 (c) experiment 3.



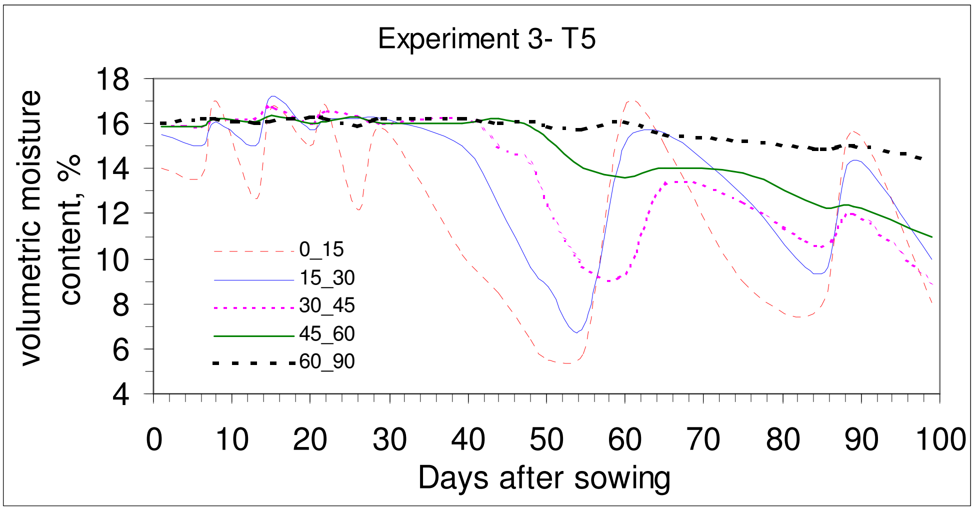




Fig 10. Temporal variation of soil moisture in wheat crop root zone at 75% MAD of available soil water ($T_5$) during (a) experiment 1 (b) experiment 2 (c) experiment 3.

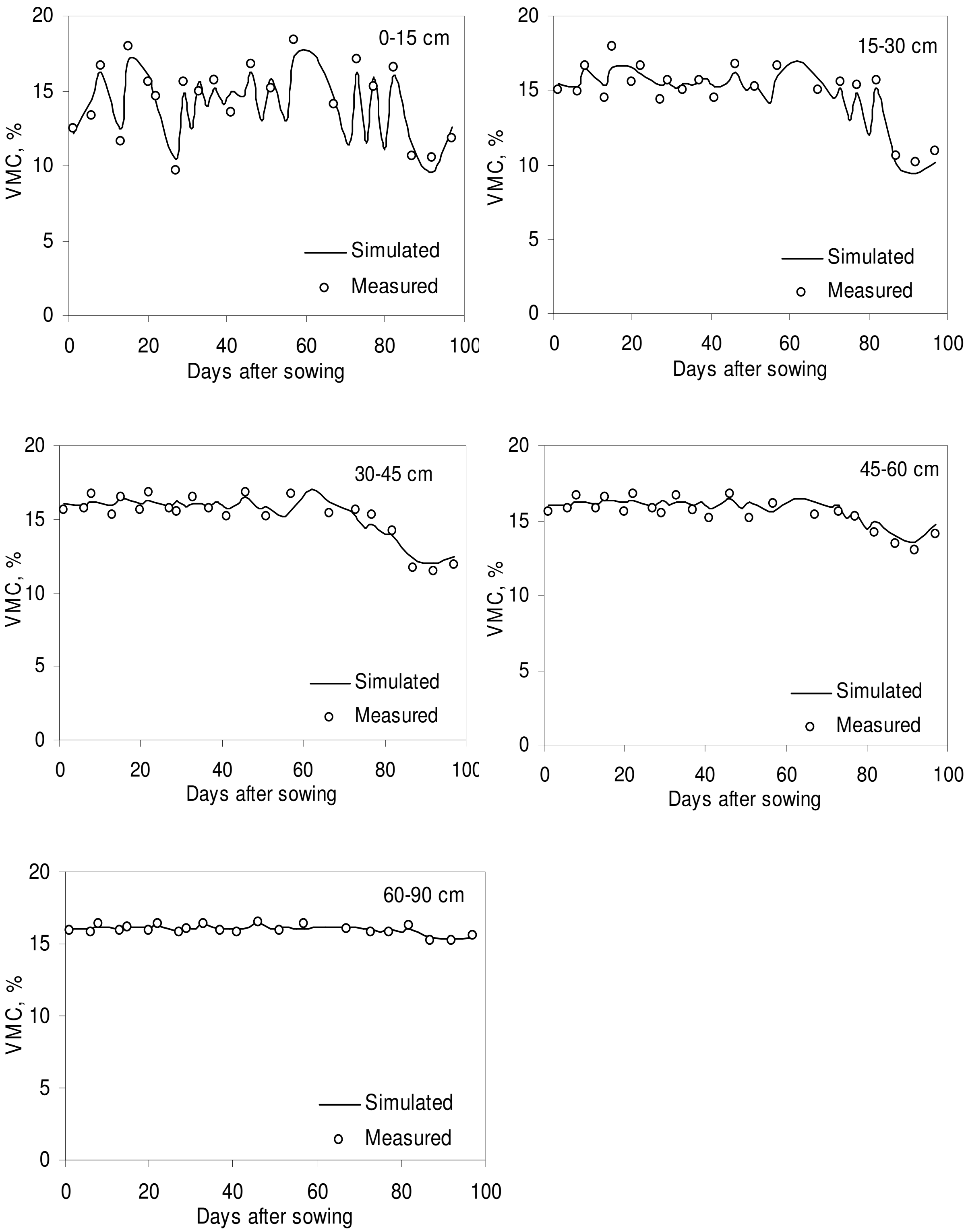



Fig 11. Depletion pattern of soil water storage of the layer 0-15cm, 15-30cm, 30-45cm, 45-60cm and 60-90cm in wheat crop field under the irrigation schedule based on 10% MAD ($T_1$) of ASW during experiment 1.

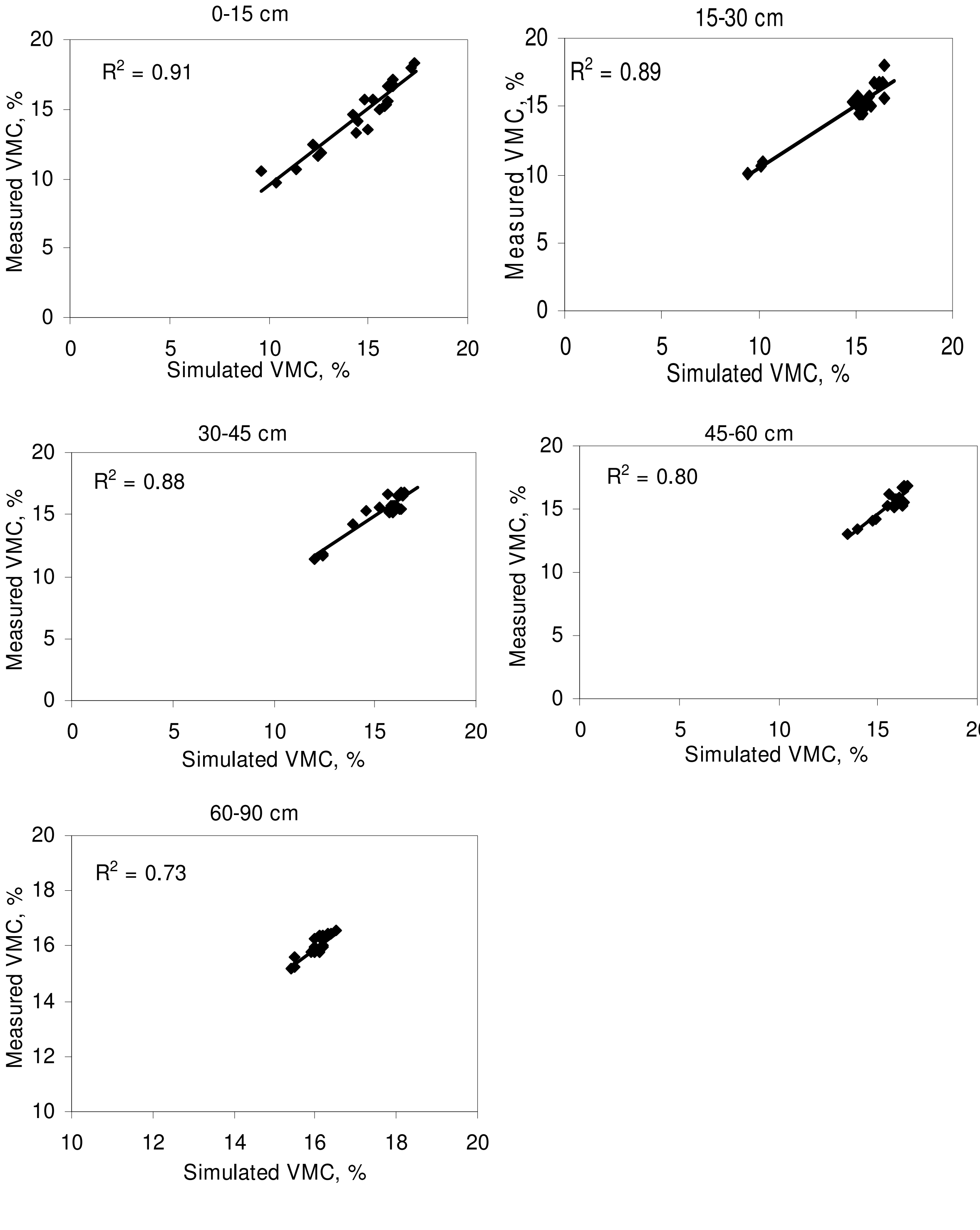



Fig 12. Measured and simulated soil profile moisture content within and below the root zone in wheat crop field under irrigation scheduling based on 10% MAD ($T_1$) of ASW during experiments 1995-96

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