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Managing Irrigation Water to Enhance Crop Productivity under Water-limiting Conditions: A Role for Isotopic Techniques

Final Report of a Coordinated Research Project

Joint FAO/IAEA Programme
Nuclear Techniques in Food and Agriculture

IAEA
International Atomic Energy Agency

MANAGING IRRIGATION WATER TO ENHANCE CROP PRODUCTIVITY UNDER WATER-LIMITING CONDITIONS: A ROLE FOR ISOTOPIC TECHNIQUES

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FINAL REPORT OF A COORDINATED RESEARCH PROJECT

PREPARED BY THE
JOINT FAO/IAEA DIVISION OF NUCLEAR TECHNIQUES IN FOOD AND AGRICULTURE

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FOREWORD

Nearly 70% of fresh water withdrawal is used for agriculture, and it is estimated that a further 19% will be needed by 2050 to meet the food demands of a larger global population. Water use efficiency, however, is currently very low — less than 40% globally. Therefore, there is an urgent need to raise efficiency by increasing crop productivity and reducing water consumption. Information on the efficiency of different irrigation technologies and the process of soil evaporation and transpiration under different agroclimatic and soil–plant management conditions is often unavailable.

The objective of this coordinated research project (CRP) was to identify methods and approaches to improve crop water productivity under water-limiting conditions using isotopic and related techniques. Keeling plots and isotopic mass balance were two methods used to partition soil evaporation and crop transpiration on account of the unique isotope signals of water vapour within the ecosystem boundary layer. Measurements of the isotope composition in the atmospheric water vapour within the canopy boundary layer or in the residual soil water over time can provide quantitative information about the sources and processes controlling water exchange in the soil–plant–atmosphere system.

Results obtained using isotopic techniques as well as those using conventional methods, such as soil moisture sensors, eddy covariance and microlysimeters, are reported in this publication. Results from the AquaCrop model, developed by the Food and Agriculture Organization of the United Nations (FAO) and used to improve irrigation scheduling and water use efficiency under different agronomic practices, are also presented.

This CRP was implemented between 2007 and 2012 following the recommendations of a consultants meeting of international experts. The research network included participants from Australia, Austria, China, Malawi, Morocco, Pakistan, Spain, Turkey, the United States of America, Viet Nam and Zambia. It was supported by research and development on extraction methodologies and analysis of hydrogen and oxygen isotopes in plant and soil samples conducted at the FAO/IAEA Agriculture and Biotechnology Laboratories, in Seibersdorf. The IAEA is grateful to all the CRP participants for their valuable contributions. The IAEA officer responsible for this publication was L.K. Heng of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture.

CONTENTS

SUMMARY

This Coordinated Research Project (CRP) on 'Managing Irrigation Water to Enhance Crop Productivity under Water-Limiting Conditions: A Role for Isotopic Techniques' established and supported a research network and teams of scientists in eleven Member States consisted of Australia, Austria, China, Malawi, Morocco, Pakistan, Spain, Turkey, United States, Viet Nam and Zambia. The main objective of the CRP was to improve crop water productivity (production per unit of water input) under water-limiting conditions. The specific objectives of the CRP were to: (i) Quantify, and develop means to manage soil evaporative losses to maximise the beneficial use of water – the transpirational component of evapotranspiration, (ii) Quantify, and develop means to improve the amount of biomass produced per unit of transpiration, and (iii) Devise irrigation and related management techniques to enhance the yield component of biomass production (Harvest Index).

The CRP aimed to improve crop water productivity under water-limiting conditions using isotopic and related techniques, by supporting Member States in their efforts to optimize water use efficiency and its sustainability as well as increasing crop yield. The proportion of water lost as soil evaporation (E) versus plant transpiration (T) relative to the total evapotranspiration (ET) can affect crop productivity at various spatial and temporal scales. The ability to accurately quantify water loss from the plant rooting zone and partitions total ET as E and T will help to evaluate the effectiveness of land and water management practices that influence E and T components. Stable isotopes of water (^{18}O and ^{2}H) and soil moisture neutron probe (SMNP) and conventional approaches such as the eddy covariance, mini-lysimetry and canopy cover determination were used to quantify components of soil evaporation and crop transpiration under different irrigation management practices, crop species and growth stages. The FAO's AquaCrop model [1, 2] was used to compare the experimental and simulated results to improve crop water productivity.

ISOTOPIC TECHNIQUES USED IN THE CRP

Two new isotopic approaches tested in this CRP were the Keeling Plot [3] and the Isotopic Mass Balance (IMB) methods [4, 5], using the stable isotopes of water (^{18}O and ^{2}H). The Keeling plot method is based on the isotopic mass balance mixing relationship of atmospheric water vapour above and below the crop canopy. Atmospheric water vapour samples taken within the mixed boundary layer were assumed to represent a mixture of isotopes and concentrations between the background atmosphere and the evaporating surface of the crop. The Keeling plot method was carried out in the Austria, China (Chinese Academy of Agricultural Sciences (CAAS)), Morocco, Turkey and Viet Nam studies. The crops tested were spring barley, winter wheat, summer maize, as well as citrus and coffee trees. The irrigation practices included drip, flood, furrow and sprinkler.

The Isotopic Mass Balance (IMB) method is based on the mass balance of water (initial and final plus water added as irrigation or rainfall and those lost as evaporation and transpiration) as well as the conservation of isotope mass balance in the system. The IMB method was applied in the China Agricultural University (CAU) study on winter wheat and spring maize under furrow irrigation and rainfed treatment.

The soil moisture neutron probe (SMNP) was used to measure soil water for irrigation scheduling and soil water balance calculation in several studies: China, Pakistan, Turkey and Zambia. In addition, the carbon isotope discrimination ($\Delta^{13}C$) was used in the Turkey study to determine the relationship between leaf, grain carbon isotope discrimination values, with grain yield and water use efficiency values.

Table 1 summarizes the crop type, irrigation treatment, and E and T partitioning method carried out by the CRP participants.

TABLE 1. A SUMMARY OF THE STUDIES CARRIED OUT BY THE CRP PARTICIPANTS

Country	Crop	Treatments	E & T methods	Experimental site
Austria	Spring barley	Rainfed	Keeling plot, capacitance sensors and AquaCrop model	BOKU Experimental Station, Groß-Enzersdorf, Vienna
China (CAAS)	Winter wheat Maize	Sprinkler	Keeling plot; eddy covariance; mini-lysimeter; SMNP and AquaCrop model	Dryland Farming and Water-Saving in Agriculture Station, Hengshui, Hebei National Precision Agriculture Station, Changping, Beijing
China (CAU)	Winter wheat spring maize	Furrow	Isotopic mass balance	Beijing Experimental Station
Morocco	Winter wheat Citrus tree	Flood and drip	Keeling plot, eddy covariance and AquaCrop model	Tensift catchment and Agafay station, Marrakech
Pakistan	Winter wheat	Flood	SMNP and AquaCrop model	NIAB Station, Faisalabad
Turkey	Winter wheat	Flood	SMNP and Keeling plot	Saraykoy Research Station, Ankara-Mürted Basin
Viet Nam	Coffee trees	Drip	Keeling plot	Dak Ha district, Tay Nguyen Plateau
Zambia	Paprika	Drip	SMNP	University of Zambia Field Station, Lusaka

FIELD VALIDATION OF ISOTOPIC TECHNIQUES FOR QUANTIFYING EVAPORATION AND TRANSPIRATION IN CROP ECOSYSTEMS

Isotopic technique for quantifying evaporation and transpiration in winter wheat and summer maize was carried out in China (the Chinese Academy of Agricultural Sciences (CAAS)) [6] using the Keeling plot method. The study showed that the proportion of evaporation to total evapotranspiration was higher in the early and late growth stages compared to mid-season stage, due to lower canopy cover during crop emergence and senescence at the end of the season (Fig. 1). Soil evaporation on average contributed 30% to total ET for both the winter wheat and maize crops (Table 2).

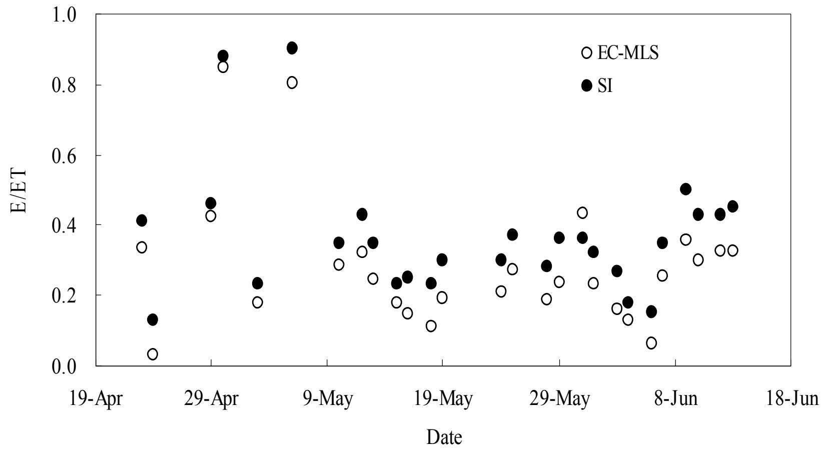

FIG. 1. Seasonal changes of the ratios of E to ET (E/ET) in winter wheat estimated by conventional (O) and isotopic (●) methods at Changping experimental station in China.

TABLE 2. THE RATIO OF SOIL EVAPORATION TO EVAPOTRANSPIATION (E/ET) FOR WINTER WHEAT AND MAIZE STUDIES CARRIED OUT BY CAAS, CHINA

Crops	Sowing-tillering	Tillering-jointing	Jointing-heading	Flowering-filling	Filling-mature	Total
Wheat	0.42	0.68	0.24	0.15	0.22	0.29
Maize	0.67		0.28	0.18	0.20	0.32

The separation of E and T from ET for winter wheat and spring maize was also carried out at the China Agricultural University, however the isotopic mass balance was used instead of Keeling plot. The study compared mulching and filming on soil surface to minimize soil evaporation losses under furrow irrigation practice (Table 3). The results showed that the proportion of soil E under furrow irrigation and with filming was similar for winter wheat, accounting approximately 22% of total ET, indicating filming in winter wheat was not as effective in reducing soil evaporation. For spring maize the proportion of soil evaporation was about 30%, a result similar to that obtained using the Keeling plot reported by CAAS. The study showed that leaving soil bare without cultivation during winter wheat and spring maize seasons contributed approximately 40% of the total ET lost as soil E [7].

TABLE 3. AMOUNT (IN MM) OF EVAPOTRANSPIRATION AND SOIL EVAPORATION IN WINTER WHEAT (WW) AND SPRING MAIZE (SM) IN 2010 USING ISOTOPIC MASS BALANCE METHOD

Crop	Conventional		Filming		Straw mulching		Bare	
	ET	E	ET	E	ET	E	ET	E
WW	147	33 (22)	92	19 (21)			56	23 (41)
SM	206	63 (31)	157	22 (12)	178	43 (24)	182	65 (38)

†Data in brackets are the % of E of total ET. WW: winter wheat; SM: spring maize

In Morocco, a study carried out in late spring on winter wheat showed that soil evaporation contributed 32% to total evapotranspiration under farmers' flood irrigation practice, when determined using the Keeling plot method. This was also simulated using AquaCrop model (Fig. 2). The finding showed that farmers' visual observation of the need for irrigation is not accurate and efficient, it results in large amount of the water applied lost through soil evaporation and deep drainage [8].

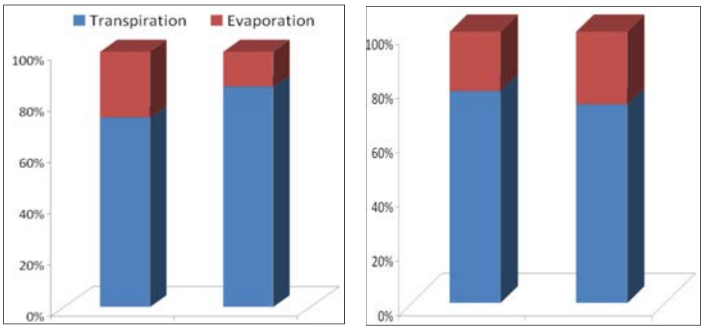

FIG. 2. Comparison of E and T of winter wheat in Morocco using the AquaCrop model (right) and isotopic (left) methods [8].

In Viet Nam, the proportion of soil evaporation and crop transpiration were also quantified using the Keeling plot method. This was carried out in a coffee plantation at bean development, bean formation, flowering and bud development and maturity stages, with and without crop residues and drip versus furrow irrigation [9] (Dang et al., 2013). The results showed that soil evaporation differed with growth stages, with evaporation the highest (53%) during maturity and canopy forming stages, and is lowest during budding, flowering and bean development stages (Table 4). However, it is driest at the budding and flowering stages as it coincided with dry period of the year when coffee requires the most water compared to other stages. The study also showed that drip irrigation combined with mulching increased the transpiration proportion of coffee plants by approximately 10% compared to furrow and no-mulch practice. The effect was minimal in the drip without mulches compared to traditional furrow and no-mulch practice (Table 5). This was probably because the trees were relatively big with canopies covering each other making solar radiation on soil surface to be almost similar in both treatments. The study showed that surface management practices could improve water use efficiency of coffee trees.

TABLE 4. THE PROPORTION OF SOIL EVAPORATION VERSUS TOTAL EVAPOTRANSPIRATION (%) OF COFFEE PLANTS BEFORE IRRIGATION FOR THE THREE IMPORTANT STAGES AS DETERMINED BY THE KEELING PLOT ISOTOPIC TECHNIQUE

Stage	E/ET (%)
Mature and canopy reforming (September–November)	53
Budding and flowering (December–February)	15
Bean development (April–August)	16

TABLE 5. PROPORTION OF E/ET OF COFFEE PLANTS IN THE FLOWERING STAGE UNDER DIFFERENT IRRIGATION PRACTICES

Irrigation practice	E as ET (%)
Furrow, no-mulch	17
Drip, no-mulch	13
Drip with mulch	6

In Turkey, the proportion of soil E and T of winter wheat before and after an irrigation event was also determined using the Keeling plot approach. The proportion of E as percent of total ET was 4% before irrigation, and 22% after irrigation, as determined from the Keeling plot method [10].

The Keeling plot approach was also tested for spring barley [11] and winter wheat [12] at the BOKU University experiment station near Vienna, Austria. Just like the experiment at CAAS in China, the laser spectrometer was set up in the middle of the crop field sampling water vapour within and above the canopy for its ^{18}O isotopic composition, partitioning ET into soil evaporation (E) and plant transpiration (T). In the spring barley study, the development of the canopy cover was monitored regularly with photographs taken from planting to harvest, and analysed with the software 'Green Crop Tracker' [13]. On the other hand, for the winter wheat study, coupling the isotopic results with those obtained using eddy covariance approach, it was possible to infer the source strengths of water vapour in the canopy from its concentration profile and canopy turbulence data through Inverse Lagrangian (IL) dispersion techniques. The study showed very good agreement between the two approaches, with the isotope analysis giving soil E as 4% of ET and the IL technique as 6% [12].

Using isotope measurements of atmospheric vapour to partition component fluxes requires accurate estimates of the isotope composition of plant-transpired water (δT). Spatial, temporal and species-level heterogeneity in δT makes this task challenging. Williams and Ewers [14] addressed the heterogeneity of gas exchange properties and microclimate of different leaves within a single complex canopy and its influence on the isotopic signature of transpired water.

CONVENTIONAL METHODS OF QUANTIFYING EVAPORATION AND TRANSPIRATION

The soil moisture neutron probe was used to determine soil water balance and subsequently the E and T components of the paprika crop [15]. Three irrigation treatments were carried out: 50, 75 and 100% ETc. in the study, soil water loss by evaporation was calculated from total evapotranspiration (ET) by subtracting transpiration (T) component from soil water balance. The study showed that, approximately 75% of ET was lost during the vegetative stage as evaporation. However, as crop grows the amount of transpiration (T) increases. The study showed that in the 100% Tc treatment, the total amount of soil E was much the highest compared to the other two treatments, however, the percentage of E/ET was approximately the same under the three treatments (Table 6), with almost 75% of total water lost through evaporation process.

TABLE 6. PARTITIONING OF ET INTO SOIL E AND T OF PAPRIKA CROP DURING VEGETATIVE STAGE. VALUES IN BRACKETS ARE PERCENTAGES OF E/ET

Treatment (% ETc)	ETc (mm)	E (mm)	T (mm)
50	153	114 (75%)	39 (25%)
75	241	179 (74%)	61 (26%)
100	285	215 (75%)	70 (25%)
Mean	226	169 (75%)	57 (25%)

In Pakistan, AquaCrop model simulating winter wheat showed that in the early growth stages soil evaporation was the main component of water losses under both rain-fed and irrigated treatments due to the low canopy cover. This evaporation component was much less under irrigation compared to rainfed treatment as the season progressed [16]. The study showed the importance of irrigation in enhancing crop growth and minimizing soil evaporation losses. In Turkey, winter wheat study showed that the proportion of evaporation as total ET increased immediately after irrigation (30% before irrigation versus 36% after irrigation) [10].

BETTER STRATEGIES TO IMPROVE THE CROP PRODUCTION PER UNIT OF WATER USED

The CRP showed that improving irrigation can be achieved by irrigating the right amount at the right time. This requires one to know the crop water requirements with a certain degree of accuracy and to be able to monitor effectively the water status of the root zone. The FAO's AquaCrop model was also used to improve irrigation scheduling and agronomic practices for efficient agricultural water use and conservation. This was carried out in China (CAAS), Morocco, Pakistan and Turkey. The paper of Fereres and Heng [17] reviews the use of remote sensing from satellites to characterize irrigation performance for benchmarking areas in need of improvement. Improving crop production per unit of water used also required nutrient input to enhance water uptake as shown in the Zambia study [15].

SIMPLE, FAST AND PORTABLE VACUUM DISTILLATION APPARATUS FOR EXTRACTING WATER FROM SOIL AND PLANT SAMPLES

A simple, fast and portable vacuum distillation apparatus (Fig. 3) was developed as part of this CRP for extracting water from soil and plant samples for isotopic analyses for the E and T separation. With water isotope analyses becoming cheaper, easier and faster (e.g. the development of the fast and accurate laser isotope analyser), the bottleneck in sample throughput is often the water extraction time instead of the isotopic analysis of water. However, most conventional extraction techniques are laborious, time consuming and involved complicated setup with specially-made glass apparatus with the needs of liquid nitrogen or dry-ice, all these can be difficult to access in developing countries. The new apparatus developed can be assembled using a commercial immersion cool, in placed of the liquid nitrogen or dry-ice for freezing water vapour [18]. The method can be easily adopted at a relatively low cost and allows large number of samples to be extracted quickly for isotopic analysis.

FIG. 3. The vacuum distillation setup consists of heating blocks, Dewar cold bath, an immersion cooler and an electronic thermometer to monitor temperature of the cold bath.

CONCLUSIONS

This CRP tested successfully the Keeling Plot and the Isotopic Mass Balance isotopic and conventional methods to quantify the soil evaporation component of water losses and determine the transpiration efficiency for several important crop species under a variety of environments. The CRP also provided improved estimates of soil E and T components and showed that better nutrient management is as important as water management for improving transpiration efficiency as shown in the studies carried out in Zambia. Both water and nutrient management should form part of plant improvement programme to enhance crop productivity in water-limited environments. FAO's AquaCrop model was successfully use to develop irrigation schedules to save water through minimising soil E and improving water use efficiency, as shown from the work of China and Pakistan. This CRP also developed a simple, fast and portable vacuum distillation apparatus for extraction water from soil and plant samples for isotopic analyses for the separation of soil evaporation which helps to reduce the bottleneck in sample throughput for many soil water and hydrology studies.

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SCHEDULING DEFICIT IRRIGATION OF WHEAT-MAIZE CROPPING SYSTEM IN NORTH CHINA PLAIN BY MEANS OF ISOTOPIC TECHNIQUE AND AQUACROP MODEL

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Abstract

Evapotranspiration (ET) and its component are often used as key parameters of crop water use efficiency. Evaporation (E) is a non-productive water loss while transpiration (T) is productive consumption. At present, there are few reliable estimates for evapotranspiration components (E&T) and water use efficiency for the wheat-maize cropping system under deficit irrigation in the North China Plain (NCP). The overall aim of this project is to separate E and T from ET for analyzing evaportranspiration components and evaluating water use efficiency under different irrigation schemes using isotopic techniques. The research furthermore relates to crop water use efficiency, ratio of leaf transpiration to evapotranspiration, and water regimes, and then schedules deficit irrigation in NCP by means of the AquaCrop model. The results showed that, under water stress conditions, the drought tolerant varieties such as SJZ8 had less water requirement (represented by K_c) and a smaller yield response factor to water deficit (represented by K_y), and higher yield and WUE than those of water stress sensitive varieties like YM20. There were significantly negatively linear relationships between water use efficiency and leaf carbon isotope discrimination. The present study also showed that E/ET estimated by on-line stable isotopic air vapour analysis system was in agreement with that by conventional method, and both methods indicated that the T/ET of wheat and maize were 70% and 68%, respectively for the whole development duration. The isotopic method of E and T separation gives rapid and reliable results, but whether it provides precise results at higher time resolutions (e.g. hour and minute) to researchers requires further investigation. The AquaCrop model is robust and has the ability to predict the soil water dynamics in the root zone profile, as well as evapotranspiration, biomass and final grain yield of wheat and maize under various water available conditions. The model was able to simulate the possibility of achieving more grain and biomass by applying less water. In other words, stable isotopic technique and the AquaCrop model can contribute to food security improvement in the water-limited areas like the NCP in China.

1. INTRODUCTION

The North China Plain (NCP) is the second agricultural production region in China. Traditional agriculture is well-developed in the area. During the past four decade years, a wheat-maize double cropping system has turned into the main cropping pattern because of its high productivity sustained by full irrigation, adequate fertilization and improvements of crop varieties [1]. However, due to limited precipitation and annual variability, agricultural productivity is low without irrigation. As a result of rapid regional development in the last two decades the competition for water has become very high. There are no sufficient surface water resources for irrigation, so groundwater has been used, causing the regional groundwater table to drop significantly. On the other hand, the demand for high crop yield has led to the application of irrigation water increasing from 100 mm in the 1950s to more than 300 mm in 2000s. This presents a serious problem for sustainable agricultural development in the region.

Deficit irrigation (DI) imposes deficits with crops reducing shoot growth but not impacting adversely on yield, and avoids deficits at critical points in their development that will affect adversely on yield-determining processes to enhance water productivity. If deficit irrigation were to be applied in the NCP, water shortages might be partially solved. Unfortunately, few farmers use DI in the region due to insufficient knowledge. It is therefore essential to develop optimal DI strategies to minimize unproductive water loss and improve crop productivity to transfer this knowledge to the farmers, the end-users.

At present, the potential to increase the water productivity of crops by maximizing the transpired fraction and minimizing soil surface losses have not been adequately examined. The use of stable isotopes to estimate evapotranspiration (ET) fluxes from vegetated areas is increasing. By complementing conventional net flux measurements (gradient or eddy covariance techniques), isotope analyses can allow partitioning of ET into its components: soil evaporation and leaf transpiration. Different irrigation techniques as well as soil management practices have potential effects on E and T components. So, the effects of different DI strategies on the water flux components using stable isotopes (^{18}O and ^{2}H), and then optimize the DI strategies to reduce the soil evaporation and enhance the leaf transpiration ratio to evapotranspiration (ET) should be evaluated.

At a farm scale evapotranspiration (ET) can be easily measured by conventional methods such as Bowen ratio [2], eddy covariance [3], gradient systems and weighting macro-lysimeters [4], but it is difficult to distinguish its components, plant transpiration (T) and soil evaporation (E), which are controlled by different mechanisms by biotic and abiotic factors [5]. Soil evaporation, an unproductive water loss, is equal to about 30% of evapotranspiration during whole plant development period under the conventional irrigation pattern in North Plain of China [4]. Partitioning evapotranspiration accurately into these two components can enhance understanding of water loss processes at the interfaces of soil-plant-atmosphere continuum (SPAC), which can help us to explore solutions to improve the crop water productivity.

Conventional methodologies for separating evapotranspiration are of four kinds: (i) combination of soil lysimeters for evaporation and sap flow sensors/chambers for plant transpiration [6]; (ii) eddy covariance systems/Bowen ratio systems/gradient systems/weighing macro-lysimeter for evapotranspiration and micro-lysimeters for soil evaporation [7]; (iii) eddy covariance systems/Bowen ratio systems/gradient systems/weighing macro-lysimeter for evapotranspiration and sap flow sensors/chamber systems for plant transpiration; (iv) theoretical methods such as the Shuttleworth-Wallace model [8], the dual crop coefficients method [9] and time series analysis [10]. Methods of the first type suffer from poor spatial representation [11] while the second and third type methods must solve the scale transformation from point to farmland, and the last ones confront the difficulty of parameters uncertainty.

The isotopic signatures of water in soil, plant and air vapour are all different especially between the isotopic concentrations of water vapour from transpiration and evaporation. This is due to the fact that lighter $H_2{}^{16}O$ molecules, which have a higher vapour pressure and binuary diffusivity compared to the heavier isotopologues (HDO or $H_2{}^{18}O$), tends to evaporate more readily from soil, leaving the soil water pools more enriched in $\delta^{18}O$ and δD. The different isotopic signals between the above two processes (transpiration and evaporation) provide the basis to separate the total water flux in the farmland [12]. With advancement in technology, it is now possible to perform continuous evapotranspiration partitioning in situ on a daily basis [14].

In various water-limited environments, low delta in the plants, indicating low carbon isotope discrimination, has been generally associated with high transpiration efficiency (TE). Carbon isotopic composition reflects the effect of the plant water status on photosynthesis throughout the growing season. Carbon isotope (^{13}C, ^{12}C) analyses in plant tissues have a potentially important role in the selection of irrigation strategies for increased water use efficiency in water-limited environments.

The Food and Agricultural Organization of the United Nations has developed a crop water productivity model named AquaCrop to ensure efficient use of water and enhance crop water productivity to meet the demand of the growing population of the world. It simulates yield response to water of herbaceous crops with the concept of normalized crop water productivity [15], and is particularly suited to address conditions where water is a key limiting factor in crop production. It attempts to balance accuracy, simplicity, and robustness, and uses a relatively small number of explicit and mostly-intuitive parameters and input variables requiring simple methods for their determinations. Under the water limited environment, in the North China Plain there are needs to maximize crop water productivity either by means of deficit irrigation or optimal irrigation. This can be realized with the help of a validated water productivity model such as AquaCrop.

The overall objectives of this study are, therefore, to measure soil water content, partition ET into the two components: soil evaporation and leaf transpiration using isotopic techniques and also to evaluate crop water use efficiency when subjected to different water regimes. Based on crop water use efficiency and leaf transpiration ratio, the optimal deficit irrigation regimes will be selected using the AquaCrop model. The specific objectives were as follows:

(1) Soil water content under the different irrigation treatments will be measured using neutron probes to estimate parameters such as crop coefficients (K_c) and yield response coefficients to water deficit (K_y). Water use efficiency (WUE) was evaluated through measurements of ^{13}C in leaves.
(2) ET of maize will be measured using eddy covariance techniques at field scale, and partitioning ET into its components: soil evaporation and leaf transpiration, will be completed using in situ continual measurements of a laser-based isotope system and a Keeling plot approach, and verifying this method using measurements of eddy covariance system and micro-lysimeters.
(3) Optimizing deficit irrigation based on crop water use efficiency and leaf transpiration ratio to ET with the support of AquaCrop model.

2. MATERIALS AND METHODS

2.1. Estimations of the crop parameters and crop water use efficiency under different irrigation levels

2.1.1. Experimental site and treatments

The experiment was conducted in the Dryland Agriculture Station, Hengshui, Hebei Province, China (37 43' N, 115 57' E., 19 m Alt.). The climate is temperate with an average temperature of 13°C and a mean annual rainfall of 500 mm. The soil at the station is classified as fluvo-aquic soil series with a loam texture and an average bulk density of 1.45 g/cm^3. The growth period of winter wheat is usually dry with about 130 mm rainfall and prominent northwest winds. In the root zone (0–200 cm), the volumetric soil water content at field capacity and wilting point were 34.7% and 16.8%, respectively.

Experiment 1

A field experiment was conducted to estimate yield response coefficient (K_y) and crop coefficients (K_c) parameters of different genotypic crops. It was carried out under a rainout shelter in 30 lysimeters with an area of 6.66 m^2 (3.33 m × 2 m) and depth of 3 m (Fig. 1). Four different irrigation levels were imposed at three growth stages of wheat and maize (Table 1). Two wheat varieties, SJZ8 and YM20, and two maize varieties, LD981 and ZD958, were sown on 7 October and 19 June in 2008, respectively.

TABLE 1. THE IRRIGATION DATE AND AMOUNT OF ALL TREATMENTS (2008.6–2009.6)

Treatments	Growth stages		
	Seedling (1)	Elongation (2)	Tasseling (3)
T_1	100	100	100
T_2	85	100	100
T_3	70	100	100
T_4	55	100	100
T_5	100	85	100
T_6	100	70	100
T_7	100	55	100
T_8	100	100	85
T_9	100	100	70
T_{10}	100	100	55

†100, 85, 70 and 55 denote the percentage of potential crop evaportranspiration ($ET_c = K_c \times ET_0$, K_c is the crop coefficient and ET_0 is the reference crop evoptranspiration). T_1–T_{10} denotes different irrigation levels.

FIG. 1. Maize-wheat water control experiments for estimating parameters of different genotypic crops.

Experiment 2

This experiment was laid out for estimating crop water use efficiency under different irrigation levels, and consisted of four main plots with an area of 1 200 m^2 (12 m × 100 m) representing the control (no irrigation, rainfed: RFD) and three treatments including full irrigation (FI), regulated irrigation (irrigated twice or three times: RDI-1 or RDI-2). Each treatment and the control had three replicated sub-plots with an area of 100 m^2 (4 m × 25 m). There was a 1-m space between main plots to minimize water exchange among treatments. The winter wheat was sown in October 2008 with density of 600 000 plants/ha. According to the rainfall amount and groundwater table, an irrigation amount of 60 mm for each application and the dates of irrigation were given (Table 2).

TABLE 2. THE IRRIGATED DATE AND AMOUNT OF ALL TREATMENTS (2008.6–2009.6)

Treatments	Irrigation amount of different wheat growing periods (mm)				Total irrigation
	Turning green	Elongation	Tasseling	Grain filling	amount (mm)
RFD					0
RDI-1	60 (March-20)				60
RDI-2	60 (March-20)			60 (May-22)	120
FI	60 (March-20)	60(April-11)	60 (May-5)		180

2.1.2. Measurements of soil water content and weather parameters

Two experiments were carried out. In Experiment 1, the volumetric soil water contents (SWC) in the center of each plot before and after irrigation, during crop growth and maturation was measured with a TRIME-FM, a quasi-time domain reflectometry (TDR) probe, at intervals of 20 cm from soil surface to 200 cm depth. The TDR was calibrated while the access tubes were installed. Meteorological data were measured in a standard automatic weather station. Variables measured included global radiation, air temperature, air humidity, rainfall, and wind speed at 2 m above ground (Fig. 2). In another experiment (Experiment 2), volumetric soil water contents (SWC) in the center of each plot before and after each irrigation or at least bi-weekly during crop growth and maturation were measured with a neutron moisture meter (NMM) (CPN Hydroprobe) at interval of 20 cm from 30 to 200 cm depth and with a portable TDR unit (Mini-Trase) in the surface 15 cm. The NMM was calibrated when the access tubes were installed. Calibration was very consistent over time and space in the plot area.

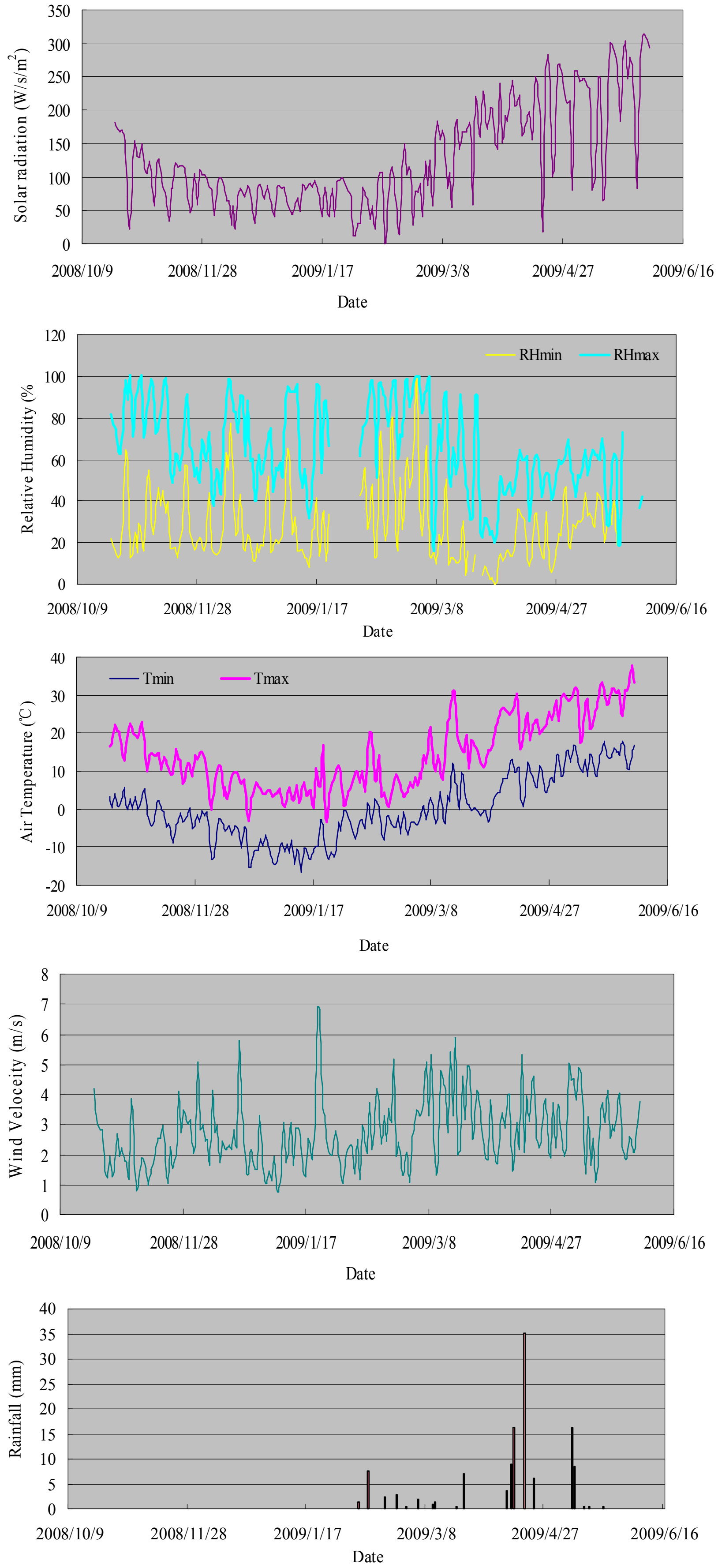


FIG. 2. The weather parameters during crop growing periods (2008–2009).

2.1.3. *Calculating methods of crop coefficients and yield response factors*

The crop coefficient (K_c) was determined from the ratio of crop evaportranspiration (ET_c) under the optimal water supply to reference evaportranspiration (ET_0) as:

$$K_c = ET_c / ET_0 \tag{1}$$

The yield response factor K_y was derived from the observed data sets by regressing the experimental evapotranspiration deficit data against the corresponding relative yield decreases. The factor K_y is defined by the ratio between the relative yield decrease and the relative evapotranspiration deficit as:

$$(1 - Y_a / Y_m) = K_y (1 - ET_a / ET_m) \tag{2}$$

where ET_a and ET_m are, respectively the actual and the maximum potential crop evapotranspiration in mm, and Y_a and Y_m are the corresponding yields in kg/ha, respectively under limited and optimal water supply.

Crop evapotranspiration under varying irrigation levels was calculated using the water balance model:

$$ET_a = I + P - D - R \pm \Delta S \tag{3}$$

where ET_a is the seasonal crop evapotranspiration, I the applied irrigation water, P the precipitation, D the drainage, R the runoff and ΔS the variation in water storage of the soil profile. All terms are expressed in mm of water in the crop root zone. The effective root depth was estimated according to crop growing stages. In addition, the water content between the effective rooting depths to 200 cm was also determined and the total water content in these layers was considered to be deep percolation. Runoff was taken to be zero since it did not occur while irrigating.

2.1.4. *Measurements of ^{13}C in leaves and water use efficiency (WUE)*

Carbon isotope determinations were performed by isotopic ratio mass spectrometry at the stable isotopic laboratory, Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agriculture Science. Water use efficiency (WUE) is the ratio of actual yield to crop water consumed. If the crop yield is expressed in kg/m^2 and the water use is expressed in m^3/m^2, then WUE has units of kg/m^3 on a unit water volume basis.

2.2. Partitioning plant transpiration and soil evaporation with stable isotope, eddy covariance and micro-lysimeter

2.2.1. *Experimental site and plant materials*

Experiment 3

The experiment was conducted in a winter wheat field at National Precision Agriculture Station, Changping, Beijing, China (40°11’ N, 116°26’ E, 43 m Alt.) (Fig. 3). The climate is temperate with an average temperature of 12°C and a mean annual rainfall of 600 mm. The growth period of winter wheat is usually dry with about 120 mm rainfall and a prominent northwest wind. The soil at the station is classified as a fluvo-aquic soil series with a loam texture and an average bulk density of 1.42 g/cm^3. In the root zone (0–150 cm), the volumetric soil water content at field capacity and wilting point were 33% and 16%, respectively. The experimental plot area is about 4.5 ha, with a length of 150 m and a width of 300 m, which meets the installation requirements of an eddy covariance system. The winter wheat was sown in October 2010 with a density of 600 000 plants/ha. During the observing period from April to June 2011, there was only about 60 mm precipitation, and the wheat was irrigated two times using sprinkler system. The amounts of irrigated water were about 75 mm and 45 mm. Precipitation, irrigation amounts and soil water content (0–200 cm) at the study site are shown in Fig. 4.

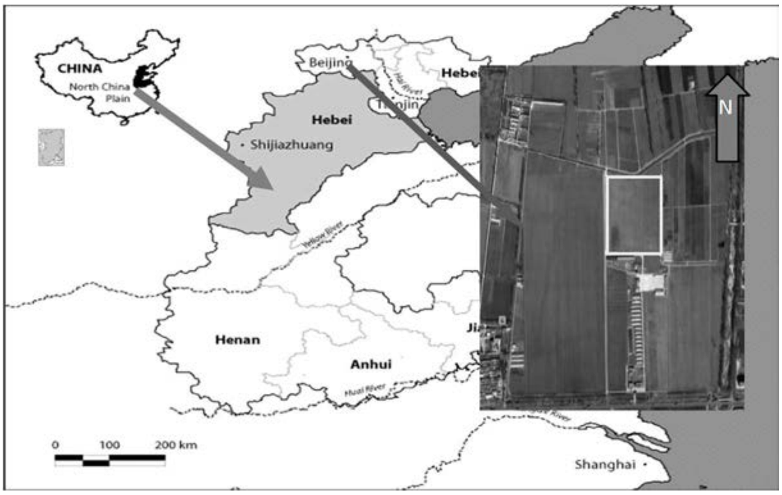


FIG. 3. Schematic diagram of the observe station and experimental plot (2011).

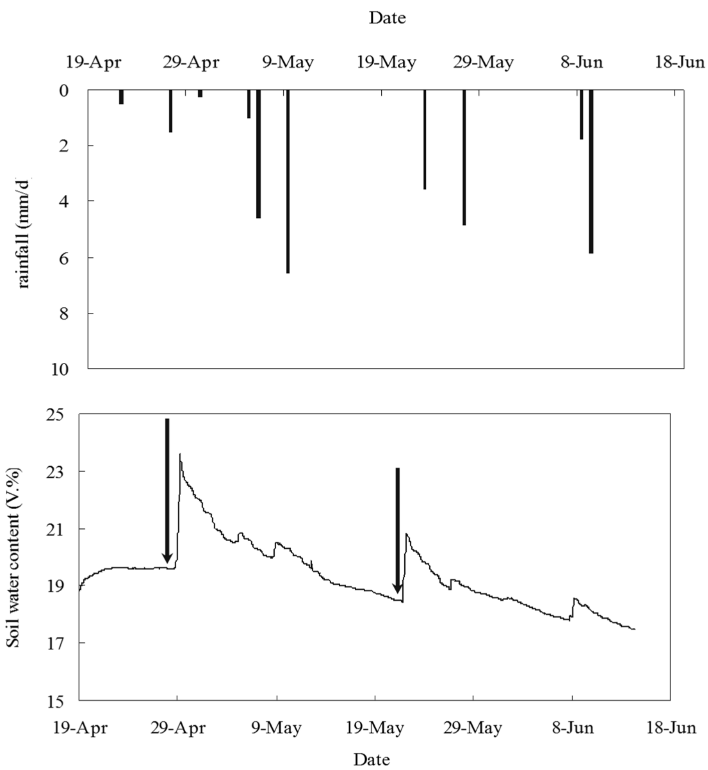


FIG. 4. Daily rainfall, irrigation, and soil water dynamic at Changping during the experimental period from April to June 2011.

2.2.2. Measurements of evapotranspiration and soil evaporation at farm scale

The study consists of an eddy covariance system installed in the middle of a winter wheat field to measure ET, with latent (LE) and sensible heat (H) fluxes measured using a LI-7500 H_2O/CO_2 analyzer and a CSAT3 sonic anemometer, respectively. Net radiation (Rn) was measured with a net radiometer while soil heat flux was measured with heat flux plates of constant thermal conductivity. In addition, soil evaporation was measured with micro-lysimeters (internal diameter of 7.0 cm and a length of 17.5 cm). Seven micro-lysimeters were installed randomly in the upstream direction of the eddy covariance system to measure daily soil evaporation. The bottom of these micro-lysimeters was capped with a steel plate to prevent free drainage of water. The soil in the micro-lysimeteres was replaced every 2-3 days to avoid any divergence from surrounding soil. Detailed information is given in [16].

2.2.3. Measurements of stable isotope ratios of vapor, soil and plant water

The isotopic signature of air (δ^2H and $\delta^{18}O$) and the vapour concentration at different heights (5, 50, 80, 120 and 160 cm) were measured using a laser spectrometer (Piccaro Inc.). Similarly, soil samples at three sites at 2, 5, 10, 15 cm depths, together with five plant stem samples were also collected at an interval of 2–3 days for extraction to determine their isotopic signatures [16].

2.2.4. Canopy cover (Cc) measurements

The canopy cover was measured using a LI-191 Line Quantum Sensor (Li-cor Ld. Com.) which uses a one-meter-long quartz rod under a diffuser to conduct light to a single, high-quality quantum sensor. Photosynthetic photon flux densities from beneath the canopy ($PPFD_b$) and above the canopy ($PPFD_a$) were measured by this sensor at five different sites. Canopy cover was calculated using the equation $C_c = 1 - PPFD_b / PPFD_a$ [16].

2.2.5 Meteorological measurements

The meteorological data (global radiation, air temperature, air humidity, rainfall and wind speed) were measured in the experimental site with a standard automatic weather station at 2 m above ground.

2.2.6. Theory description

The isotopic mass balance approach was used to partition ET into its components, farmland surface contribution to atmosphere moisture composed of water from soil evaporation E and water from plant transpiration T:

$$ET = E + T \tag{4}$$

If these two components are isotopically distinct, isotopic mass balance is:

$$\delta_{ET} = \delta_E + \delta_T \tag{5}$$

where δ is the isotopic composition, subscripts ET, E, and T stand for evapotranspiration, evaporation, and transpiration, respectively. Assuming that $F_S = E/ET$, and substituting $T = ET - E$ from Eq. 4 into Eq. 5 and rearranging, F_s is obtained:

$$F_S = \frac{\delta_{ET} - \delta_T}{\delta_E - \delta_T} \tag{6}$$

where δ_{ET} is estimated using Keeling mixing model [17], δ_E is estimated using the Graig amd Gordon[18] model, and δ_T is estimated from the measured isotopic values of stem water.

2.3. Calibration of the aquacrop model and its application for optimizing deficit irrigation

2.3.1. Calibration and validation of AquaCrop model

Before the model application, its calibration and validation are important steps, which involve a comparison between independent field measurements and output predicted by the model. Soil water content over the rooting depth, canopy cover, above-ground dry biomass and grain yield were considered in this study for model evaluation. The performance of the calibrated model was evaluated against the independent data sets (experimental data of 2009–2010 cropping season) which were not used for model calibration. Different statistical indices including coefficient of determination (r^2), regression 1:1, absolute and normalized root mean square error (RMSE) and agreement (D-index) were employed for comparison of predicted against observed data. The coefficient of determination (r^2) expressed in percent is given in Eq. 7.

$$r^2 = \frac{\sum_{i=1}^{n}(O_i - O_{avg})(P_i - P_{avg})}{\sqrt{\sum_{i=1}^{n}(O_i - O_{avg})^2}\sqrt{\sum_{i=1}^{n}(P_i - P_{avg})^2}} \tag{7}$$

where P_i and O_i refer to predicted and observed values of the study variables, respectively, e.g. canopy cover (C_c), biomass, grain yield and evaportranspiration. P_{avg} and O_{avg} are the mean of the predicted and observed variables, respectively. The normalized RMSE is expressed in percent (Eq. 7, 8).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2} \tag{8}$$

The normalized RMSE gives a measure (%) of the relative difference between simulated and observed data. The simulation is considered excellent when the normalized RMSE is less than 10%, good if the normalized RMSE is greater than 10% and less than 20%, fair if the normalized RMSE is greater than 20% and less than 30%, and poor if the normalized RMSE is greater than 30% [19]. The index of agreement (D-index) was estimated in Eq. 9. According to the d-statistic, the closer the index value is to one, the better the agreement between the two variables that are being compared and vice versa:

$$d = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P_i'| + |O_i'|)^2} \tag{9}$$

where P_i is the predicted data, O_i is a measured observation, $P'_I = P_{iv} - P_{avg}$ and $O'_I = O_i - O_{avg}$.

2.3.2. Optimizing deficit irrigation of a maize-wheat cropping system using AquaCrop model

After model validation, the model was used to evaluate the effects of different irrigation scenarios (crop growth stages and depth of water applied) on grain yield, evapotranspiration and water use efficiency (WUE). Using weather data from the study area from 1971 to 2010, they were classified as: wet (W), normal (N), and dry (D), depending on the amount of annual precipitation (W>third quartile, first quartile<N<third quartile, D<first quartile). The soil characteristics of Changping station (Table 3) were used for the simulation. WUE is a useful indicator for quantifying the impact of irrigation scheduling decisions with regard to water management. In a crop production system, WUE is defined as the ratio between the grain yield (GY) and cumulative crop evapotranspiration (ET).

TABLE 3. SOIL PHYSICAL CHARACTERISTICS OF THE EXPERIMENTAL SITE

Depth (m)	Moisture content			Bulk density (g/cm^3)	K_{sat} (mm/d)	CN
	PWP (vol.%)	FC (vol.%)	Sat (vol.%)			
0.0–0.3	15.0	31.0	46.0	1.45	250.0	75
0.3–0.5	16.0	33.0	48.0	1.49	250.0	
0.5–0.6	10.0	22.0	41.0	1.53	500.0	
0.6–0.7	23.0	39.0	50.0	1.44	100.0	
0.7–1.5	39.0	48.0	55.0	1.42	2.0	

†FC, field capacity; PWP, permanent wilting point; TAW, total available water; Sat, water content at saturation; Ksat, saturated hydraulic conductivity; CN, curve number of rainfall-runoff.

3. RESULTS AND DISCUSSION

3.1. The crop parameters and crop water use efficiency under different irrigation levels

3.1.1. Crop coefficients (K_c) for different genotypic wheat and maize

Variation of wheat Kc at the eight crop stages was between 0.35 and 1.20 for variety YM20, and between 0.40 and 1.15 for variety SJZ8 (Fig. 5A). The growth-stage-specific Kc for variety YM20 was 0.35 at emergence, 1.20 at flowering and 0.50 at maturing. These values were smaller at the initial growth stage and larger at the middle and end growth stage to those from variety SJZ8. Our values are also larger at all growth stage than those (1.0 for the peak K_c) reported at Kimberly, Idaho [20] and quite similar to those given in FAO-56 paper [21].

Figure 5B showed a two-order parabolic trend of Kc for different stages during the whole season of maize. Kc increased from the seedling to filling stages, and then gradually declined. Kc for variety ZD 958 at the seedling, jointing, flowering, and maturity stages were 0.65, 0.96, 1.10, and 1.02, respectively. The values were smaller at all growth stage than those from variety LD981. These results are also larger at the initial growth stage and smaller at the middle and late growth stages than those from plastic mulched spring maize at Wuwei, Gansu [22]; and similar at the initial growth stage and smaller at the middle and late growth stages to those from summer maize at Shijazhuang, Heibei [4].

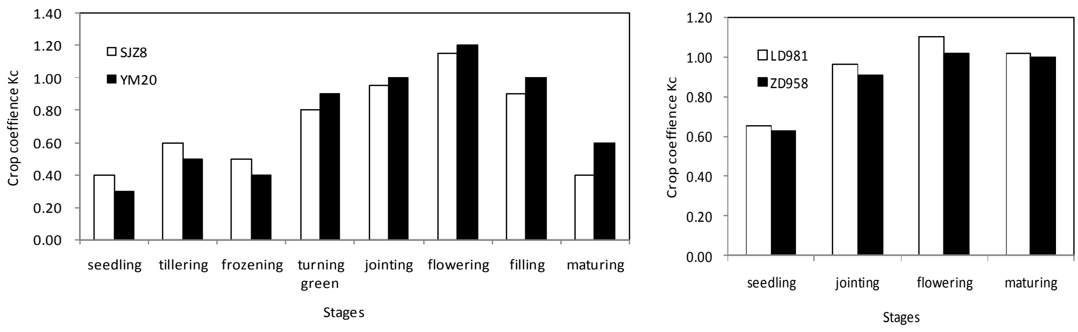


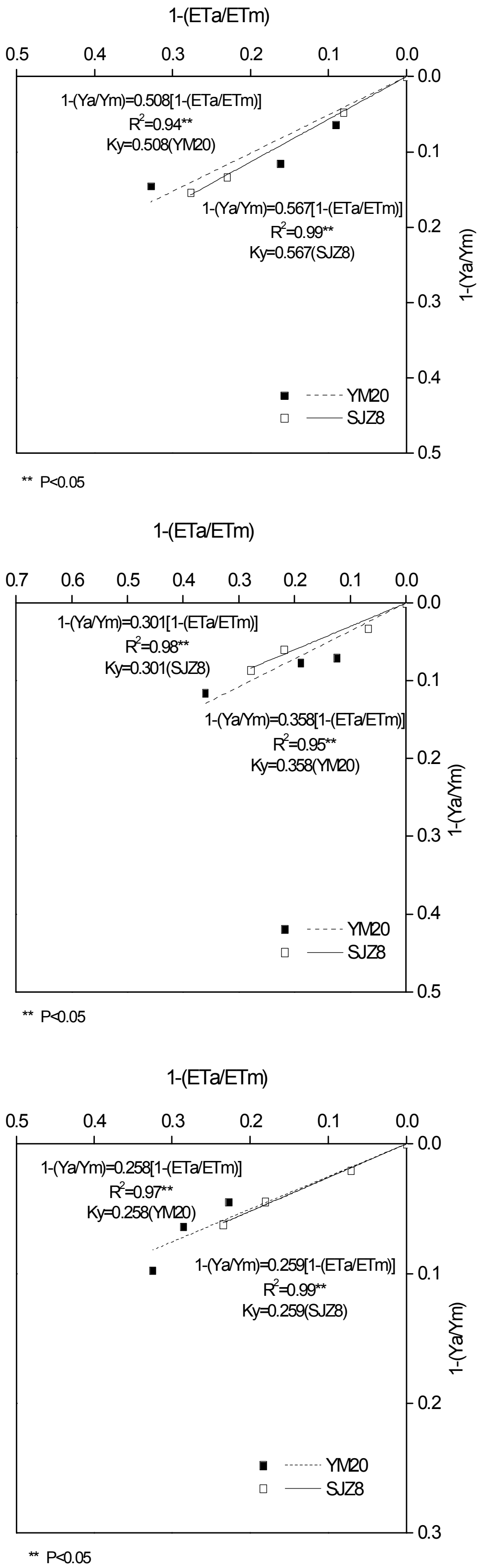
FIG. 5. Crop coefficient for two genotypes of winter wheat (left) and summer maize (right).

3.1.2. Yield response to water (K_y) for different genotype wheat and maize

The effects of water deficits on yield at each growth stage were different for wheat and maize. The experimental data sets relative to the crop evapotranspiration deficit ($1 - ET_a / ET_m$) did not exceeding the value of 0.5 and the corresponding yield decreases ($1 - Y_a / Y_m$) were used to derive the K_y factor (Eq. 2) at three growth stages. Larger deficits were not considered following the recommendations of the model authors [23]. The data sets were organized according to the maize variety used and regressed at different stages separately, as shown in Fig. 6 for winter wheat, and in Fig. 7 for the maize.

The highest yield response effect of wheat was in jointing to booting stage, with yield response factors of both genotypes with values of 0.508 and 0.567, respectively, while the lowest effect was in turning-green stage (Fig. 6). Different results were obtained for both varieties: a K_y value of 0.258 with a coefficient of determination R^2 of 0.97 (n = 4) for the YM20 and K_y of 0.259 with R^2 of 0.99 (n = 4) for SJZ8 at the turning green stage; a value for K_y of 0.508 with a coefficient of determination R^2 of 0.94 (n = 4) for the YM20 and K_y of 0.567 with R^2 of 0.99 (n = 4) for SJZ8 at the turning green stage; a value for K_y of 0.358 with a coefficient of determination R^2 of 0.95 (n = 4) for the YM20 and K_y of 0.301 with R^2 of 0.98 (n = 4) for SJZ8 at the turning green stage.

As for maize, the highest effect was at the flowering stage while the lowest effect was at the jointing stage (Fig.7). Different results were obtained for both varieties: a value for K_y of 0.34 with a coefficient of determination R^2 of 0.99 (n = 4) for the ZD958 and K_y of 0.40 with R^2 of 0.97 (n = 4) for LD981 at jointing stage; a value for K_y of 1.20 with a coefficient of determination R^2 of 0.95 (n = 4) for the ZD958 and K_y of 1.40 with R^2 of 0.95 (n = 4) for LD981 at the flowering stage; a value for K_y of 0.64 with R^2 of 0.92 (n = 4) for the ZD958 and K_y of 0.45 with a coefficient of determination R^2 of 0.94 (n = 4) for LD981 at the filling stage. There was significant difference between yield response factors of both genotypes during flowering stage, which were 1.40 and 1.20 respectively. The value for K_y of 1.2 is closer to that proposed in the literature [24].



A

B

C

FIG. 6. Yield response factor (K_y) of different wheat genotypes to water deficits in different stages: (A) Turning green stage; (B) Jointing through booting stage;(C) Flowering through filling stage.

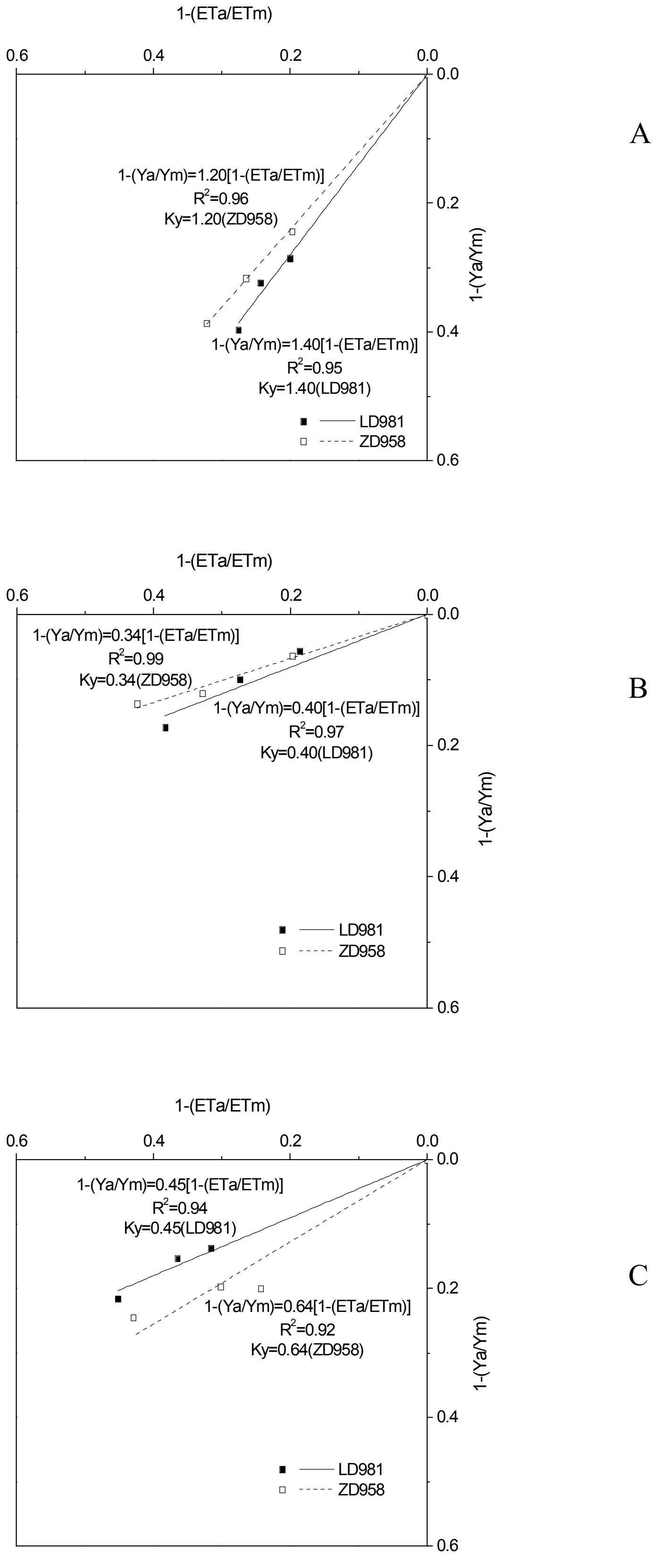


FIG. 7. Yield response factor (K_y) of two maize varieties to water deficits in different stages: (A) Jointing stage; (B) Flowering stage; (C) Filing stage.

3.1.3. Yield, water use and water use efficiency for different genotypes of wheat

The yield and water use efficiency of different wheat varieties (KM1 and SJZ8) showed that for the KM1 variety, the yield under RDI-2 treatment was not significantly smaller than those of SFI, but for SJZ8, the yield and water use efficiency of RDI-1 were superior to other treatments (Table 4). Fig 8 shows that there were significantly negatively linear relationships between water use efficiency and leaf carbon isotope discrimination with coefficients of determination R^2 of 0.946 (n = 4) for the KM1 and R^2 of 0.751 (n = 4) for the SJZ8 under four water levels. These results suggested that leaf carbon isotope discrimination could indicate crop water use efficiency.

TABLE 4. SOIL WATER BALANCE AND WATER USE EFFICIENCY OF WINTER WHEAT

Varieties	Treatment	Water use at different wheat growing stage(mm)					Total water use (mm)	Yield (kg/hm^2)	Water use efficiency (kg/m^3)
		Seedling	Turning green	Elongation	Tasseling	Grain filling			
KM1	RFD	66.3	37.5	46.1	38.1	48.1	236.1	5320.4	2.25
	RDI-1	66.3	60.8	74.9	75.7	84.7	362.4	6773.1	1.87
	RDI-2	66.3	61.6	73.2	67.4	101.4	369.9	7652.9	2.07
	SFI	66.3	70.2	87.4	97.4	117.7	439.0	7684.5	1.75
SJZ8	RFD	63.1	40.3	49.2	73.5	56.9	283.0	5295.6	1.87
	RDI-1	63.1	66.5	76.7	82.3	83.0	371.6	6715.5	1.81
	RDI-2	63.1	67.5	76.8	89.2	97.7	394.3	6849.5	1.74
	SFI	63.1	78.3	98.5	93.1	107.7	440.7	7566.5	1.72

†RDI denotes Regulated deficit irrigation; RFD denotes Rain-fed, and SFI full irrigation.

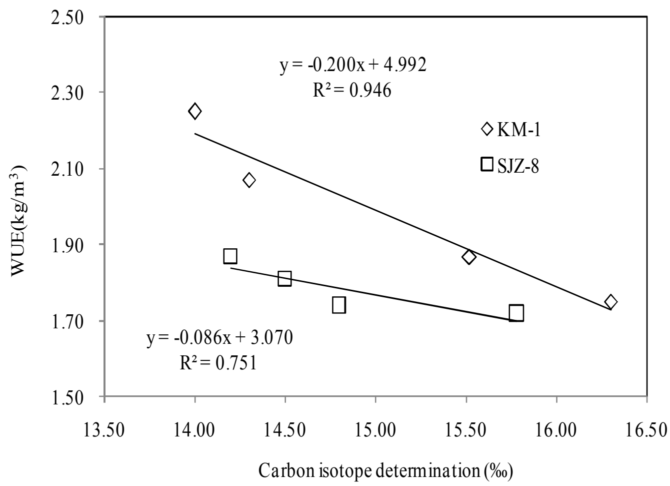


FIG. 8. The relationships between water use efficiency and leaf carbon isotope discrimination for two wheat varieties under four water levels.

3.2. **Partitioning plant transpiration and soil evaporation**

3.2.1. Temporal dynamics of $\delta^{18}O$ composition in air vapor at different heights

Figure 9 shows that the $\delta^{18}O$ composition of air vapour in the winter wheat field changed with precipitation & irrigation (P + I), vapour pressure deficit (VPD) and net solar radiation (R_n) at two heights (0.05 m, 1.60 m) from April to June in 2011. The $\delta^{18}O$ of the lower layer (0.05 m) was higher than that of the higher layer (1.60 m) because the $\delta^{18}O$ composition of vapour derived from soil evaporation and atmosphere background are very different. The difference between the low (0.05 m) and high (1.60 m) layers was about 0~10.0‰, and was related to the weather condition. These were similar to the isotopic composition distribution of vapour in a forest [25]. The stable isotope of air vapour $\delta^{18}O$ were about –45.00‰ to –5.00‰ during the observing period. In the precipitation and irrigation periods the average daily stable isotopic of vapour $\delta^{18}O$ decreased quickly, and then to the maximum gradually because of isotopic fraction effects of soil water evaporation. This was consistent with Yuan's [26] results. Through data statistical analysis, the results showed that $\delta^{18}O$ composition of air vapour at two heights correlated significantly with VPD and R_n with average correlation coefficients about 0.696 (n = 1250，$\alpha<0.001$) and 0.704 (n = 1250，$\alpha<0.001$).

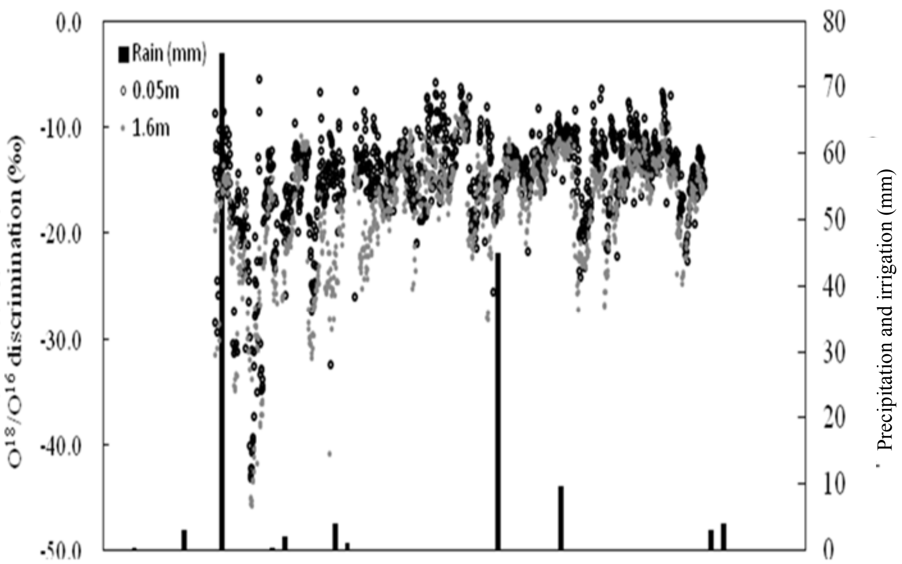


FIG. 9. The dynamics of vapor stable composition ($\delta^{18}O$) during the experimental period (2011).

3.2.2. The ratio of soil evaporation to evapotranspiration estimated by eddy covariance–microlysimeters method

The evapotranspiration (ET) and soil evaporation (E) estimated by eddy covariance and microlymeters are shown in Fig. 10. Evapotranspiration (ET) increased at the initial stages of wheat, stabilized in the middle of growth period, and decreased in late growth period. During the whole observation period the maximum and minimum of evapotranspiration (ET) were 7.2 mm/d and 1.5 mm/d, respectively, which occurred on 25 May and 21 April, respectively while soil transpiration (E) was 2.4 mm/d and 0.4 mm/d, respectively.

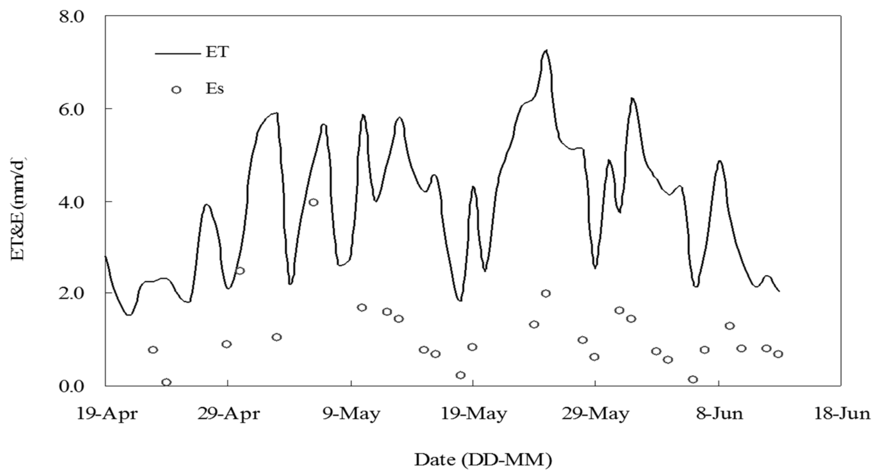


FIG. 10. Dynamics of evapotranspiration (ET) and soil evaporation (E) estimated by eddy covariance and micro-lysimeters during the experimental period (from April to June, 2011).

3.2.3. The ratio of plant transpiration to evapotranspiration estimated by isotopic method and its comparison with EC_MLS method

Gradients in atmospheric moisture content and isotopic composition through the profile of canopy boundary layer were observed during the experimental period. Linear regressions were fitted to the midday (11:00–15:00) data to estimate δ_{ET}, the isotopic composition of the ET flux (Fig. 11). There was a significant relationship between the inversion of atmospheric moisture content and isotopic composition of water vapour, suggesting that application of Keeling plot method in estimation of the isotopic composition of the ET flux from continuous measurements by water vapor stable isotopic analysis system is feasible in wheat fields of the North China Plain.

According to the isotope fractionation coefficients and the Craig-Gordon model for stable isotope composition of soil evaporation, the stable isotope composition (δ_E) of soil evaporation in the wheat field and various parameters were estimated in Table 5. The δ_E of soil evaporation was between –30‰ to –50‰, which is smaller than δ_S of the soil water, indicating isotope fractionation effect during the soil vaporation process. These results are consistent with the findings of Yuan et al. [26].

Using stable isotope compositions of the wheat field evapotranspiration (δ_{ET}), soil evaporation (δ_E) and the crops stem (δ_T), E/ET was estimated with Eq. 3 and compared to the values estimated by the conventional method (Fig. 12A). E/ET in the winter wheat field in the early and late growing seasons was higher than that in the middle growing season because of heavy canopy cover in the middle season. The estimated E/ET by the stable isotopic method was about 19.67% higher compared with combining eddy covariance and the mini-lysimeter method. There was a significant agreement between the estimated E/ET by the stable isotopic and the conventional method ($R^2 = 0.8468$, n = 27) (Fig. 12B). These results were similar to the findings obtained by [27].

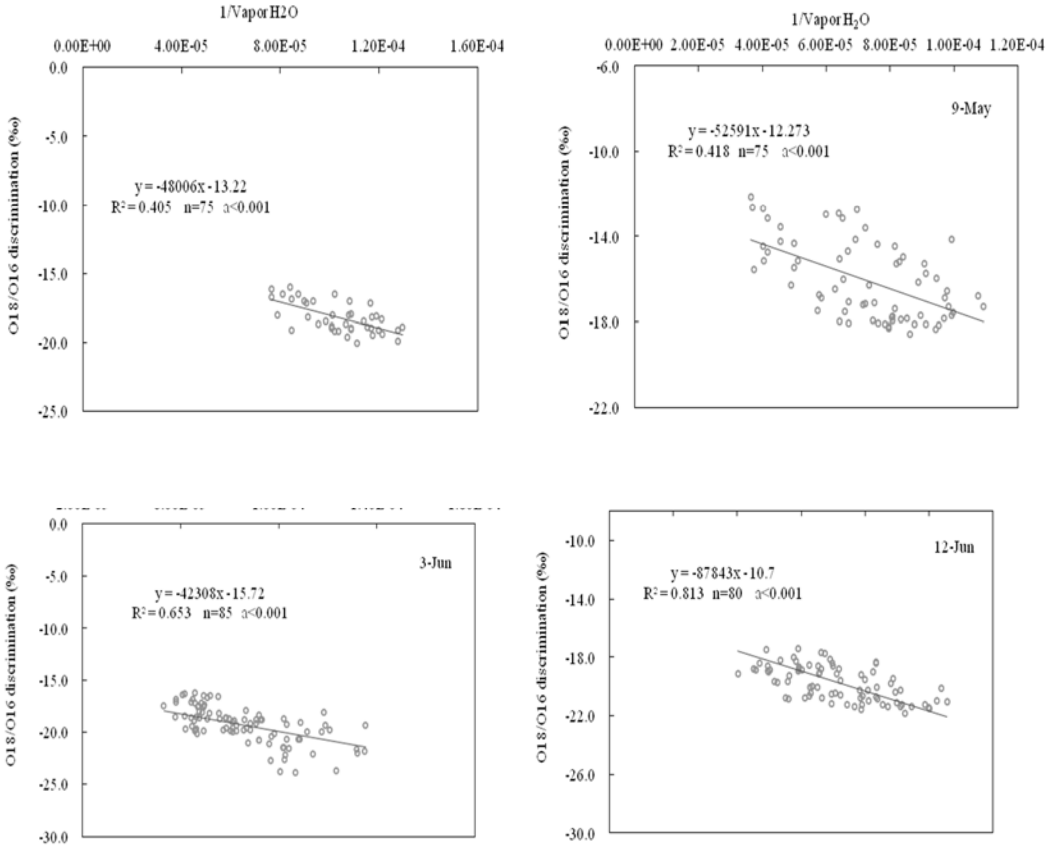
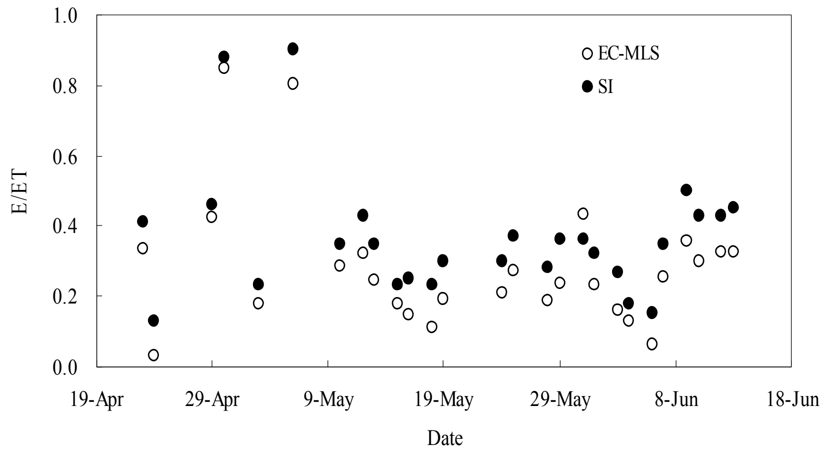


FIG. 11. Daytime Keeling plots of water vapor monitored by WRDS at different heights above the ground in the selected days forδ^{18}O.

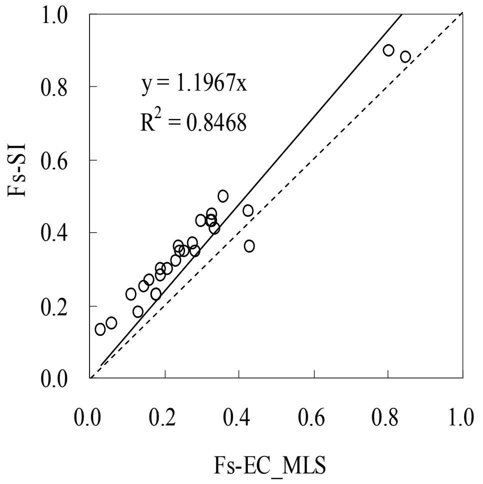
TABLE 5. PARAMETERS OF THE CRAIG-GORDON MODEL AND THE ESTIMATED VALUES OF EVAPORATION FLUX δ_E IN WHEAT FIELD ON SELECTED DAYS

Date	$\alpha_{L\text{-}V}$	$\varepsilon_{L\text{-}V}$	h	$\Delta\xi$(‰)	δ_v(‰)	δ_S(‰)	δ_E(‰)
4-23	0.9800	19.957	0.260	21.105	-27.48	-5.32	-46.83
4-30	0.9883	11.702	0.509	14.020	-18.54	-10.05	-48.16
5-6	0.9867	13.274	0.471	15.132	-12.96	-9.33	-47.39
5-9	0.9882	11.798	0.433	16.160	-15.75	-10.11	-43.51
5-18	0.9932	6.753	0.674	9.536	-11.73	-5.47	-53.02
5-22	0.9914	8.565	0.608	11.220	-15.59	-12.42	-42.71
5-28	0.9924	7.571	0.672	9.521	-11.48	-9.70	-37.45
5-31	0.9948	5.219	0.646	9.990	-18.65	-10.63	-48.12
6-3	0.9956	4.433	0.354	18.519	-15.68	-6.63	-33.56
6-6	0.9964	3.566	0.712	8.286	-11.04	-9.05	-36.58
6-9	0.9967	3.298	0.776	6.264	-11.05	-5.92	-55.82
6-12	0.9974	2.631	0.481	14.687	-18.47	-10.87	-29.89

†$\alpha_{v\text{-}l}$, the equilibrium fractionation factor for liquid–vapor exchange of H_2O; $\varepsilon_{v\text{-}l,}$ another convenient form of $\alpha_{v\text{-}l}$; h, the soil relative humidity; $\Delta\xi$, kinetic fractionation factor; δ_v, the vapour water δ^{18}O isotopic value obtained by Picarro instrument; δ_s, the average isotopic values of water at the soil surface; δ_E, estimated value of water vapour from soil evaporation.



A



B

FIG. 12. Seasonal changes of the ratios of E to ET (Fs) estimated by conventional (O) and isotopic (●) methods (A), and the relationship between the two parameters (B) at Changping in the 2011 experimental period.

3.2.4. The relationship between E/ET and canopy cover (C_c)

The ratio of soil evaporation to evapotranspiration (E/ET) is controlled by canopy cover, the wetted area of the soil surface layer and weather condition. Fig. 13 shows the fitted curve between E/ET estimated by the conventional method and crop canopy cover (C_c). There was a significant negative-lineally relationship between average E/ET and C_C with correlation coefficients (R^2 = 0.936, n = 7), indicating that E/ET decreased with increasing C_c because solar radiation reaching the soil surface decreased with increasing crop leaf area.

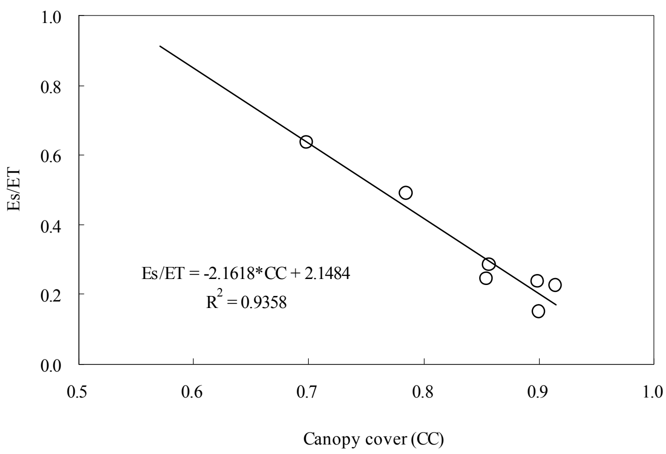


FIG. 13. The relationship between E/ET estimated by the eddy covariance plus micro-lysimeters method and canopy cover (C_c) during the experimental period (from April to June 2011).

3.2.5. The ratio of transpiration to evapotranspiration (T/ET)

The ratio of transpiration to evapotranspiration (T/ET) is often controlled by canopy cover, wetted surface layer soil water and weather conditions. T/ET in the early and late growing seasons was smaller than that in the middle growing season because of heavy canopy cover in mid-season (Table 6). Overall, T/ET in the wheat field was higher than that of the maize field.

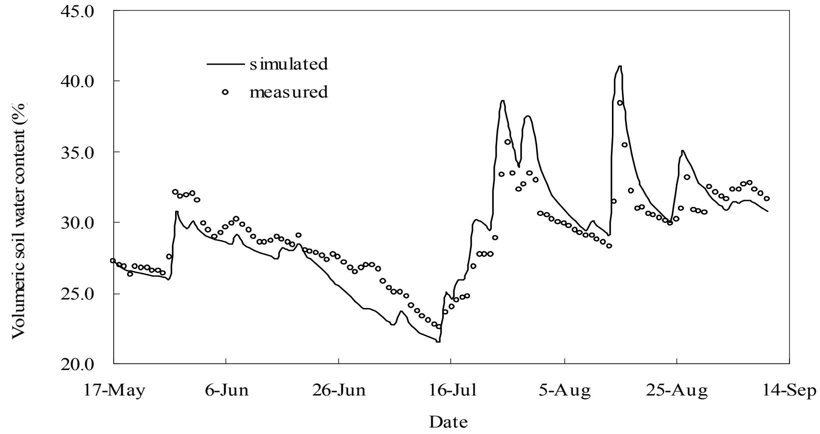
TABLE 6. THE RATIO OF PLANT TRANSPIRATION TO EVAPOTRANSPIATION (T/ET)

Crops	Sowing-tillering	Tillering-jointing	Jointing-heading	Flowering-filling	Filling-mature	Total
Wheat	0.58	0.32	0.76	0.85	0.78	0.71
Maize	0.33		0.72	0.82	0.80	0.68

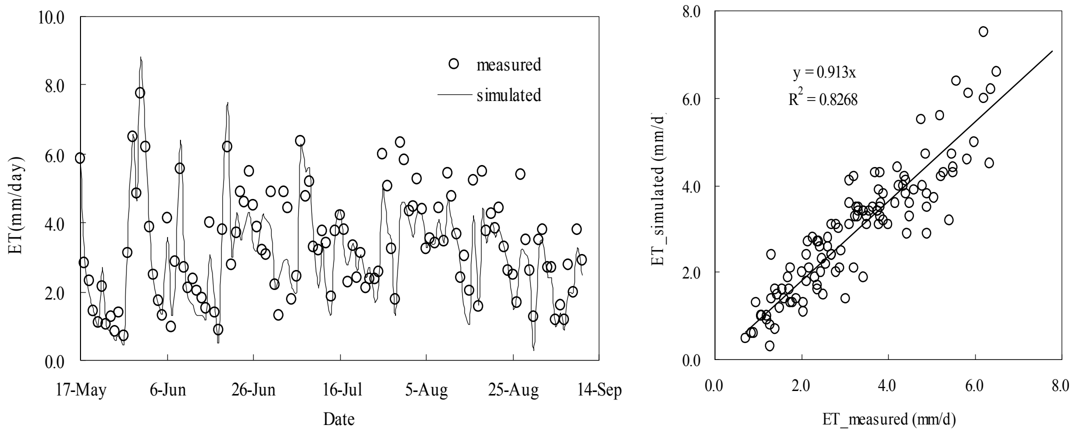
3.3. Optimizing deficit irrigation of maize-wheat cropping system with the help of the aquacrop model

3.3.1. Validation of the Aquacrop model

Simulated soil water content in the 0–200 cm soil profiles over time showed similar trends to the measured values with a coefficient of determination (r^2) of 0.56 (n = 117), an overall RMSE of 1.97% and relative RMSE of 6.79%, and a D-index (the index of agreement) of 0.92 (Fig. 14A). The simulated evapotranspiration (ET) showed similar trends as values estimated from the eddy covariance system (R^2 = 0.827, n = 117) with an overall RMSE of 0.7 mm/d and relative RMSE of 21.35%, and a D-index (the index of agreement) of 0.94 (Fig. 14B). The simulated biomass showed similar trends as estimated values from plant samples (R^2 = 0.9820, n = 8) with an overall RMSE of 1.92 Mg/hm^2 and a relative RMSE of 15.07%, and a D-index (the index of agreement) of 0.93 (Fig. 14C). The simulated final biomass yield, seed yield and harvest index (HI) were close to the measurements with relative differences of 4%, 4% and 8.0%, respectively.



A



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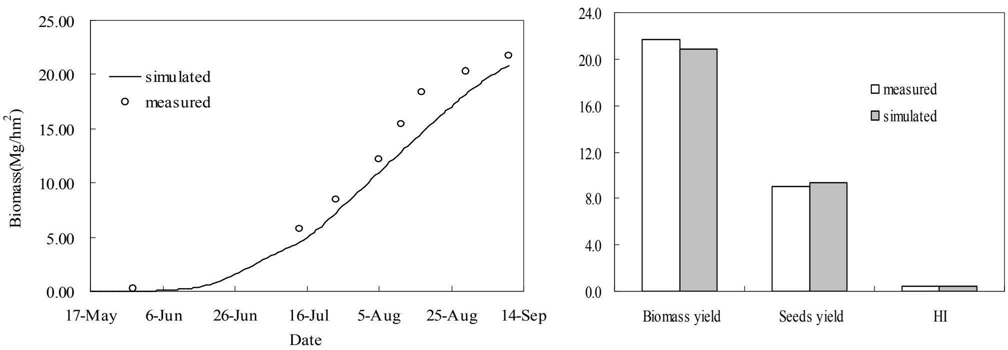

C

FIG. 14. (A) Simulated and observed soil water content; (B) evapotranspiration; (C) sequential above ground biomass and grain yield of maize grown in the 2011 cropping season.

3.3.2. Optimizing deficit irrigation of a maize-wheat cropping system using the AquaCrop model

A long-term simulation experiment (1971–2010) was carried out to investigate the most reasonable irrigation schedules for the double cropping system in the NCP (Table 7). The simulated grain yield, WUE, and drainage averaged over this period for various irrigation schedules in the wheat-maize double cropping system are presented in Fig. 15. The results showed that the total grain yield and soil water drainage of wheat maize cropping system increased with irrigation amount, but WUE decreased. Among all the simulated treatments, the grain yield and soil water drainage of WPJP was biggest, but WUE was smallest. Irrigation scheduling should take into account the interactions between maize and wheat seasons on soil water balance to achieve higher yield and WUE in the double cropping systems. The most effective irrigation strategies for wheat–maize rotation in the NCP should not only improve the WUE, but also mitigate agricultural pressures on the environment, such as the decline in groundwater levels. According to these results, in the wet year, two irrigations at planting and jointing stages of wheat and no irrigation at growth stages of maize are recommended for the double cropping system; in the normal year, two irrigations at planting and jointing stages of wheat and one irrigation at planting of maize; and in the dry year, three irrigations at planting, jointing and booting stages of wheat and one irrigation at planting of maize should be applied (Table 8).

TABLE 7. IRRIGATION SCENARIOS FOR LONG TERM SIMULATION 1971–2010

Hydro-type of year	Treatments	Effective rainfall (mm)	Irrigation (mm)	Wheat				Maize
				Planting	Jointing	Booting	Filling	Planting
Wet	WPJ	560	120	1	1	0	0	0
	WPJP	560	180	1	1	0	0	1
Normal	NPJP	440	180	1	1	0	0	1
	NPJBP	440	240	1	1	1	0	1
Dry	DPJBP	350	240	1	1	1	0	1
	DJBFP	350	300	1	1	1	1	1

†(a) the experimental station is located at Changping. (b) effective rainfall coefficient is 0.8. (c) ‘0’, ‘1’ denote irrigation and no-irrigation, respectively.

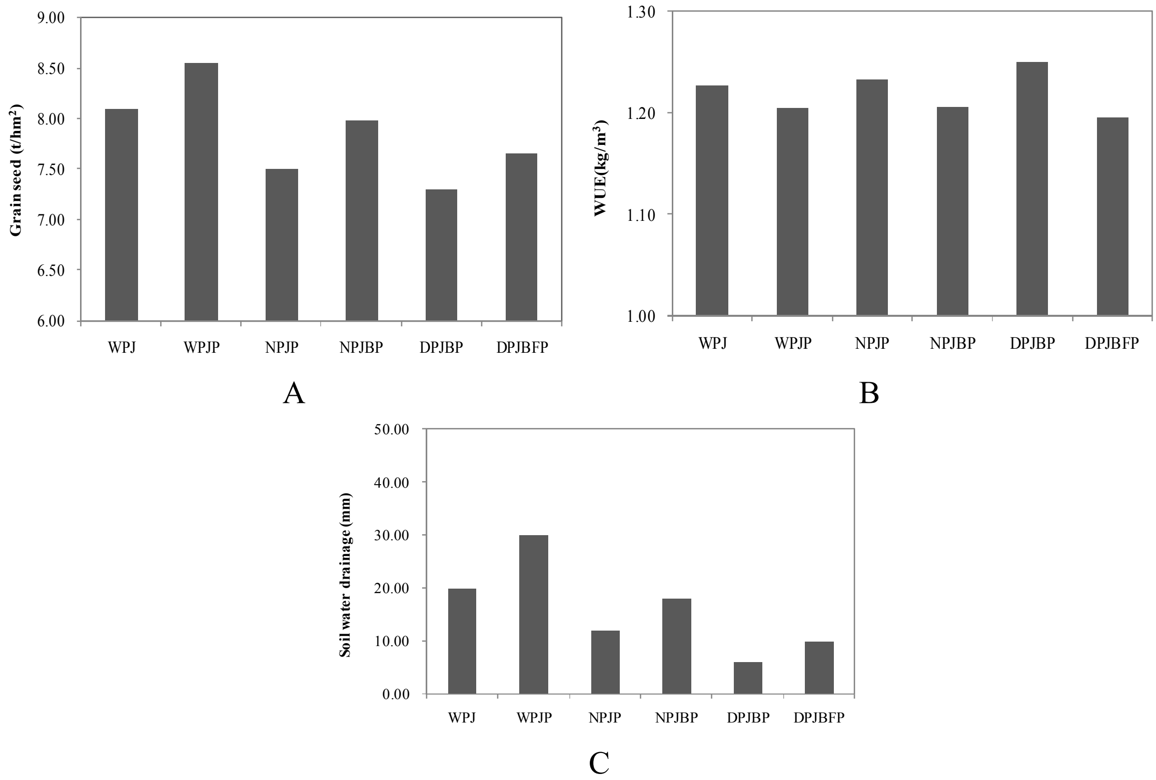

FIG 15. (A) The simulated grain yield; (B) QUE; and (C) drainage over the representive hydrological years from 1971 to 2010 for various irrigation schedules in the wheat-maize double cropping system.

TABLE 8. THE OPTIMAL DEFICIT IRRIGATION SCHEDULING FOR THE WHEAT-MAIZE CROPPING SYSTEM OF NCP

Hydro-type of year	Effective rainfall (mm)	Irrigation (mm)	Wheat	Maize
Wet	560	120	Planting, Jointing	no
Normal	440	180	Planting, Jointing	Planting
Dry	350	240	Planting, Jointing, Booting	Planting

†Irrigation patterns for wheat and maize are border and furrow irrigation respectively.

4. CONCLUSIONS

The purpose of this research was to determine the parameters (K_c and K_y) for winter wheat and summer maize grown in the North Plain China, and to estimate the ratio of E to ET with the help of conventional and isotopic methods, and then based on these results validate the Aquacrop model. Finally, the optimal irrigation scheduling in the region was generated using the AquaCrop model together with long-term historical meteorological data.

Our results showed that K_c and K_y values can vary in different varieties and crop development stages. Grain yield and WUE were also different in different varieties and water supply levels. For the drought-resistant variety, SJZ8, it has smaller K_c and K_y, and higher yield and WUE than the water-stress sensitive varieties like YM20. Carbon isotopic discrimination of crop components such as leaf and stem could be used as indicators of water use efficiency. This hypothesis was verified in our experiment. It was found that there were significantly negatively linear relationships between water use efficiency and leaf carbon isotope discrimination.

The present study also showed that the estimated E/ET by real-time stable isotopic air vapour analysis system relates significantly to that using conventional method, and therefore, demonstrated that partitioning of ET into its components by the isotopic method is feasible and reliable in the North Plain China. The method gives rapid and reliable results, but whether it provides precise results at higher time resolutions (hour, minute and second) requires further investigation.

The Aquacrop model has robust ability to predict soil water dynamics in the root zone profile, as well as evapotranspiration, biomass and final grain yield of wheat and maize under various water available conditions. This model can also be used in the assessment of irrigation strategies. The model was able to provide options of achieving more grain and biomass by applying less water. This result may help to partially solve the food crisis through increasing grain yields especially in water-limited regions similar to the NCP.

Totally, combining the isotopic technique and the Aquacrop model will make huge contributions to global food security improvement in water-limited areas like the NCP.

ACKNOWLEDGEMENTS

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FIELD EXPERIMENTAL RESULTS ON EVAPOTRANSPIRATION OF SPRING BARLEY AT GROSS-ENZERSDORF, BOKU UNIVERSITY, VIENNA

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Abstract

A field experiment was carried to determine the components of evapotranspiration (ET) of spring barley under rainfed conditions. The study was carried out at the experimental station of University of Natural Resources and Life Sciences, Vienna (BOKU) in Groß-Enzersdorf, outside Vienna. The study showed that daily ET of spring barley calculated using FAO-Penman-Monteith method was comparable with lysimeter measured values during the different growing stages. Similarly, daily evaporation and transpiration determined using isotopic technique (Keeling plot method) corresponded well with those simulated using AquaCrop model. A novel method to take standardized canopy cover photos on a camera with a stand was developed as part of this study.

1. INTRODUCTION

The climatic water balance of an area, defined as rainfall minus potential evapotranspiration, is a major factor determining agricultural production. Under semi-arid conditions evapotranspiration exceeds rainfall at least temporarily. In agricultural areas suffering from water scarcity, irrigation may be necessary in order to guarantee appropriate yield (and quality) of agricultural products [1],[2]. In Europe approximately 8 % of the agricultural area is irrigated [3], in Austria it is app. 1 % [4]. Nevertheless, in situation where excessive exploitation of water resources such as rivers and aquifers occurs, the quality and quantity of these resources will be affected [5]. Effective use of water, either from rainfall or irrigation is often a key challenge, it is therefore important to have strategies for saving water which includes the reduction of unproductive losses to the atmosphere and to groundwater.

Water (vapour) fluxes from soil to atmosphere are described by the basic hydrological processes of evaporation (E) and transpiration (T), where the former refers to vapourization from an uncovered soil surface and the latter term refers to transport of water through a plant. While transpiration is correlated to crop production, evaporation is often considered unproductive losses of water. Within a canopy cover, both E and T processes usually occur at the same time and are therefore referred to as evapotranspiration (ET). However, its fractional amounts shift during crop growth: When the plants (and thus their leaves and roots) are small water is predominately lost by evaporation, whereas later during the vegetative period transpiration increases until it becomes the dominating process. To recognize these processes provides a basis for improving agricultural water management.

The main objective of this study was to assess the components of evapotranspiration of spring barley under rainfed conditions.

2. MATERIALS AND METHODS

The studies were carried out at the experimental station of University of Natural Resources and Life Sciences, Vienna (BOKU). It is located in Groß-Enzersdorf (48°12'N, 16°34'E; 157 m), in the north-eastern part of Austria, at the boundary of one of the main crop production areas of the country. The region is influenced by a semi-arid climate with app. 550 mm mean annual precipitation, and 10°C mean temperature [6]. The soil at the experimental plots is a deep sandy loam over gravel. The plots were planted with spring barley; the study period corresponded with its vegetative period in March 2011. Measurements were carried out by means of a lysimeter facility, soil water sensors, and an isotopic laser analyzer. Furthermore, soil water balance calculations and a crop water model were utilized; reference evapotranspiration was estimated based on weather data. The latter were obtained from the local meteorological station of the Austrian Zentralanstalt für Meteorologie und Geodynamik.

2.1. Lysimeter facility

Two lysimeters were utilized to determine evapotranspiration of spring barley and reference evapotranspiration of grass, respectively. The main part of each lysimeter is a cylindrical vessel with an inner diameter of 1.9 m (surface area = 2.85 m^2) and a hemispherical bottom with a maximum depth of 2.5 m packed with sandy loam soil (0-140 cm) over gravel (140–250 cm) [7]. A weighing system registered mass changes in a certain time interval that equal changes of soil water ΔW, because the mass of the lysimeter vessel and the solid soil remain the same. Seepage water (SW) was measured at a free draining outlet at the bottom of the lysimeter by means of a tipping bucket [8]. With precipitation (P) from the ZAMG standard pluviograph, evapotranspiration (ET) was calculated from a simple water balance equation (Eq. 1).

$$ET = P - SW \pm \Delta W \qquad (1)$$

2.2. Soil water sensors

EnviroSCAN probes (ES) were installed in the lysimeter and in the field plot. EnviroSCAN (Sentek Pty Ltd, South Australia) is a multi-sensor capacitance probe measuring water content at different depths of a soil profile [9]. A support rod is fitted with several sensors, and inserted into a PVC access tube installed in the soil. Each sensor consists of two conductive rings acting as capacitor with the surrounding medium (solid soil, air and water) as dielectric. Variations of capacitance are due to variations in the dielectric of the surrounding medium – due to the fact that dielectric constant of water (app. 80) is dominant compared to soil (4–8) and air (1). The frequency of oscillation is proportional to the ratio of air and water in the soil [10]. This principle is also known as Frequency Domain Resonance (FDR). Sensor readings were normalized to a so-called Scaled Frequency $SF = (F_a - F_s) / (F_a - F_w)$, where F_a is the sensor-specific reading in air, F_w is the reading in water, and F_s is the frequency reading in moist soil. F_a and F_w were determined for each sensor in the laboratory. Soil water content θ_{ES} was calculated from SF by means of a standard default calibration relationship (Eq. 2), which generally delivers adequate results for common soil types [11][12]. Data were measured, processed, and stored in a standard RT6-logger from Sentek Company, from which the actual database was downloaded frequently.

$$SF = 0.1957\ \theta_{ES}^{0.4040} + 0.0285 \qquad (2)$$

A probe with 16 sensors measuring changes of profile water content (ΔW) down to 160 cm depth was installed in each lysimeter, and four probes were installed in the field, at a distance of approximately 100 m from the lysimeter station. Each field probe contained eight sensors, measuring soil water content changes down to 80 cm depth.

2.3. Reference evapotranspiration

With the FAO ET_0-Calculator [13], the reference ET [14] for the study site was determined based on weather data from the local station of the Zentralanstalt für Meteorologie und Geodynamik (ZAMG). The required weather data were obtained from the ZAMG. Additionally, ET_{ref}-data were taken from the grass lysimeter.

2.4. Canopy cover

Plant water uptake (transpiration) is directly correlated to the percentage of canopy cover. Hence, the development of the canopy cover was monitored photographically from planting to harvest. For that reason, pictures were taken on a regular basis and analyzed with the software 'Green Crop Tracker' [15].

To take canopy cover photos, a camera was fixed to a mount that was connected to the arm of a stand via a wire rope. The stand was equipped with a bubble level for vertical positioning. The exact position of the stand was marked in the field (Fig. 1).

In order to fulfill the requirements for image processing, all photos were taken with the same camera and focal length, and they were taken downwards, at the same distance (1 h) (Fig. 1).

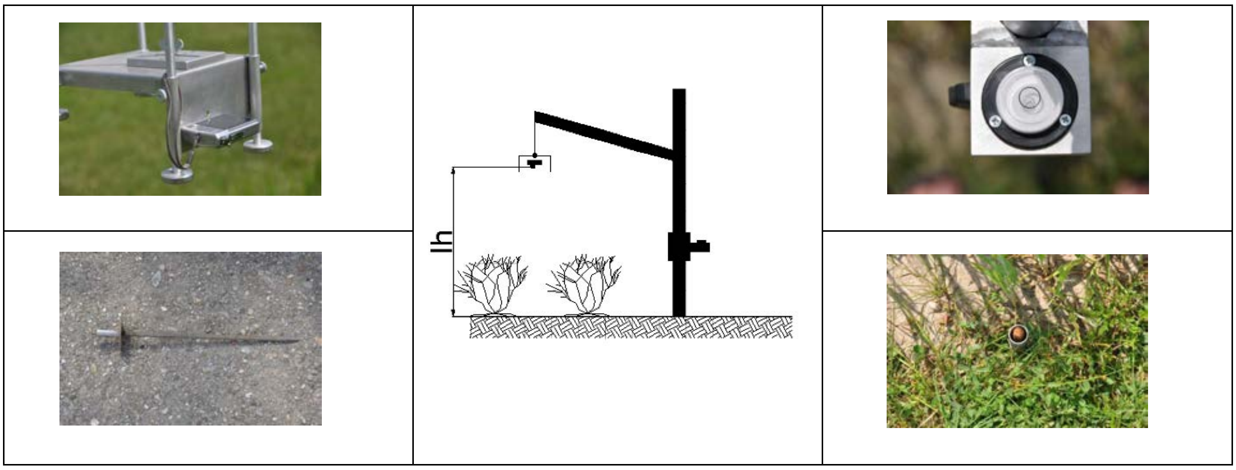


FIG. 1. Developed stand with the camera mount and a bubble level for vertical positioning.

Image processing was carried out for all photos from each crop. The digital pictures were analyzed and the vegetation green cover fractions were calculated with the 'Green Crop Tracker' software. In cases of different light or water conditions the automatic analysis of the photo series were avoided and pictures were worked out by hand. In that case the ratio between soil and canopy cover can be calculated from the whole picture or from a defined cycle (Fig. 2).

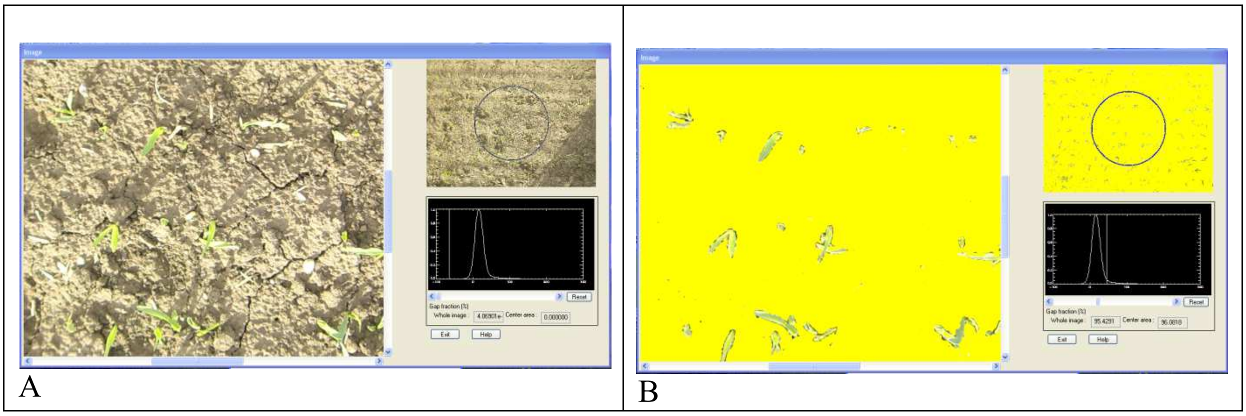


FIG. 2. Image processing with 'Green Crop Tracker': original photo (A), and processed photo with soil (yellow) and canopy cover (rest) (B).

2.5. Crop water model

AquaCrop is a simulation model developed by the FAO that helps to understand the relation between plant available water and crop production [16]. One of the outputs of AquaCrop was the proportion of evaporation E and transpiration T. The model requires weather data, soil texture and crop characteristics as basis for modeling soil water balance. The daily results of ET_0 and canopy cover served as input data for the program AquaCrop [17][18].

2.6. Isotopic field analysis

A Cavity Ring-Down Spectroscopy laser isotope analyzer (Picarro Inc.) and the Keeling-plot approach were used to partition evapotranspiration into the E and T components. Water vapour isotope measurements were carried out at five heights (0.05, 0.5, 1.1, 1.7 and 2.3 m) above and within the barley crop. In addition, soil and plant samples were collected and extracted for $\delta^{18}O$ and $\delta^{2}H$ isotopic compositions. By assuming that transpiring vegetation is under isotopic steady state, the isotopic values of stem water were taken as the transpiration vapor (δ_T) while the isotopic ratio of evaporating water vapor from soil surface (δ_E) was calculated using the Craig and Gordon model [19]. The total evapotranspiration flux can be partitioned into the E and T components if the isotopic compositions of ET (δ_{ET}) is known, this can be determined using the Keeling plots which is a mass balance mixing relationships [20] where the isotopic values of water vapour samples at different heights are plotted against the inverse of the concentration of the water vapour, with the y-intercept reflecting the isotopic values of ET [21].

Finally, the fractional contribution of transpiration F_T (%) to the evapotranspiration flux is calculated using:

$$F_T\ (\%) = (\delta_{ET} - \delta_E)/(\delta_T - \delta_E) \times 100 \qquad (3)$$

where δ_{ET} is the isotopic composition of evapotranspiration vapour, δ_E the isotopic composition of vapour from soil evaporation and δ_T is the isotopic composition of the transpiration vapour sources.

3. RESULTS AND DISCUSSION

In Table 1 the growing parameters (sowing, harvest, biomass and yield) of spring barley in the field and on a weighing lysimeter are shown.

TABLE 1. GROWING PARAMETERS OF SPRING BARLEY ON THE FIELD AND ON THE LYSIMETER

Spring barley	Field plot	Lysimeter
Sowing date:	15.03.2011	24.03.2011
Sowing density:	300 plants/m^2	300 plants/m^2
Crop Dev. Stages - Init./Dev./Mid/Late (days):	21/25/48/24	21/25/48/27
Harvest date:	08.07.2011	20.07.2011
Final grain yield:	4.80 t/ha	4.40 t/ha
Biomass (calc. with HI = 0.44):	10.9 t/ha	10.0 t/ha

Table 2 gives an overview of the climatic data and ET_0 on a monthly basis. ET_0 ranges from 0.4 mm/d in the cold season up to 4.5 mm/d in the summer time.

TABLE 2. MEAN DAILY WEATHER DATA (TEMPERATURE T, REL. HUMIDITY RHD, WIND VELOCITY WV AT 2 M, SOLAR RADIATION RAD) AND CALCULATED ET_0 FOR 2011

	T	RHD	WV 2m	RAD	Eto
	°C	%	m/s	MJ/m2.day	mm/day
Jan	0,7	84	2,0	3,2	0,4
Feb	0,4	74	2,6	6,5	0,9
Mar	6,4	67	2,2	11,1	1,7
Apr	13,2	67	2,4	16,6	3,0
May	15,8	66	2,2	22,7	4,0
Jun	19,8	69	2,4	21,7	4,5
Jul	19,7	70	2,6	17,0	3,8
Aug	21,2	70	1,6	18,2	3,8
Sep	18,2	69	1,8	13,7	2,8
Oct	10,2	77	1,9	7,5	1,3
Nov	3,3	85	1,7	3,2	0,5
Dec	3,8	77	2,2	2,1	0,7

The soil water content from the beginning of May to the middle of June from the lysimeter balance (LYS-BAL) and the FDR sensors in the lysimeter (LYS-FDR) show similar characteristics (Fig. 3). The same holds for the LYS-FDR from 0–80 cm compared to the field-FDR (Fig. 3). Nevertheless, the water depletion is much higher in the lysimeter; thus, it can be assumed that plant water uptake occurred in deeper soil layers (probably down to 1.4 m and more).

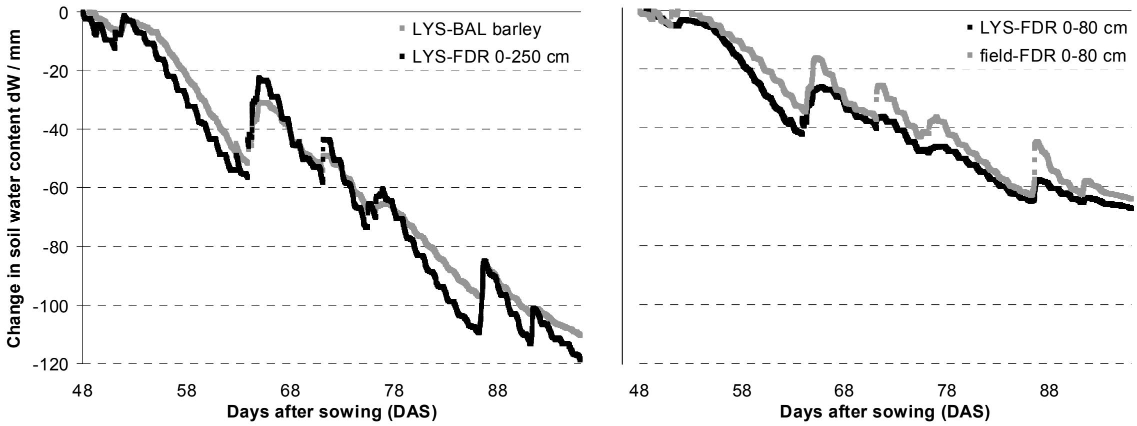


FIG. 3. Comparison of the soil water content under spring barley during the middle crop development stage in the lysimeter (A) and soil water content in the lysimeter (from 0–80 cm) and in the field measured using the FDR sensor (B).

Calculated (FAO-PM) and measured (LYS grass) mean daily ET_{ref} delivered similar results during the respective growing stages (Fig. 4A). The evapotranspiration of spring barley (ET_c) determined by means of the lysimeter water balance (LYS-BAL) delivered reasonable values too (Fig. 4A). The resulting crop coefficients ($k_c = ET_c/ET_{ref}$) for the respective crop development stages are: 0.53/0.79/1.14/0.47. Since the FDR sensors in the field (field-FDR 0–80 cm) did not detect the entire zone where plant water uptake occurred (as mentioned above), the ET_c during the middle growing phase is considerably underestimated (Fig. 4B). Consequently, a simulated water balance based on calculated ET seems to be more reliable than the field-FDR measurements in the given case. However, this has to be taken into account regarding the modeling, e.g. AquaCrop.

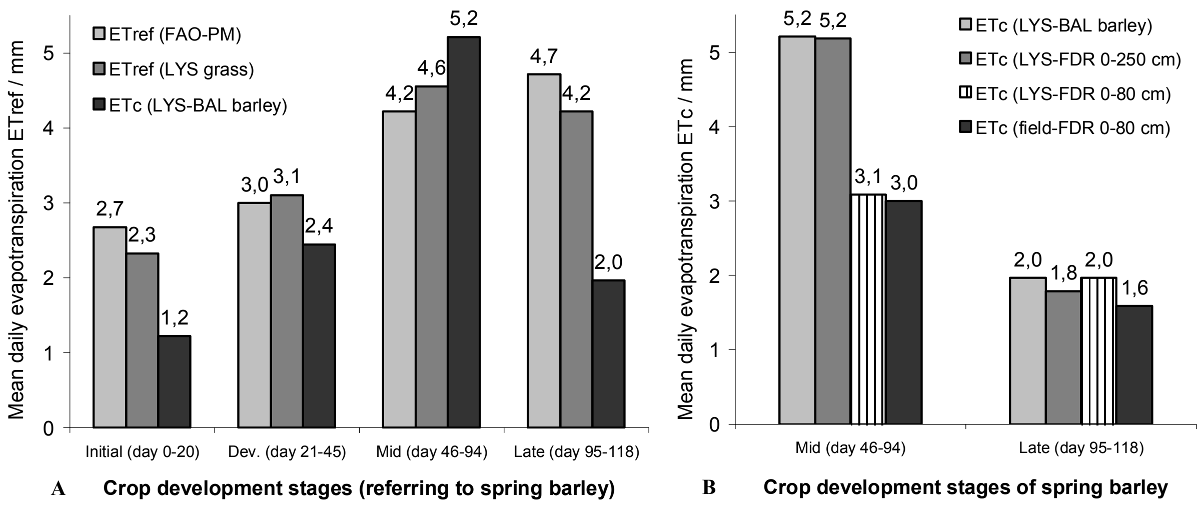
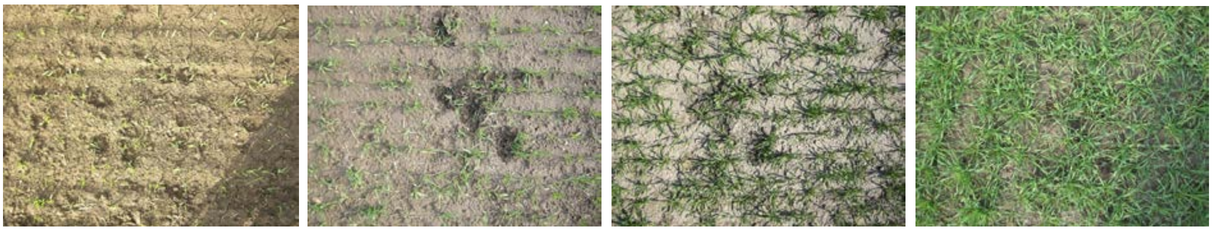


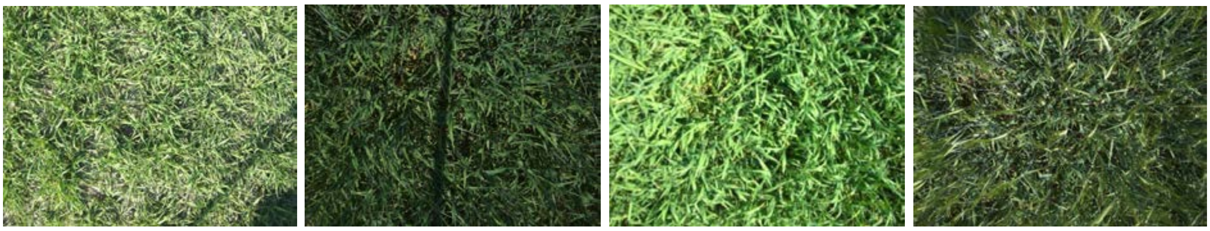
FIG. 4. (A) Calculated (FAO-PM) and measured mean daily ET_{ref}, and mean daily ET_c of spring barley on the lysimeter; (B) Mean daily ET_c during mid and late growing phase on the lysimeter and on the field plot.

The calculation of evaporation and transpiration of spring barley with AquaCrop was used with the actual daily weather data and canopy cover for year 2011.

However, the time series of the canopy cover of spring barley in Fig. 5 gives an impression of the problems of uneven lighting conditions. A photo taken in bright sunlight delivers different results as a photo under diffuse light conditions. Also different soil water conditions at the surface may influence the results. The pictures were taken more or less weekly, depending on the crop development (Fig. 5).



05.04.2011 (DAP 21)   15.04.2011 (DAP 31)   21.04.2011 (DAP 37)   27.04.2011 (DAP 43)



05.05.2011 (DAP 51)   19.05.2011 (DAP 65)   25.05.2011 (DAP 71)   07.06.2011 (DAP 84)

FIG. 5. Development of the canopy covers of spring barley.

The canopy was covering the soil with 5 % at the beginning of April (DAP 16), and then there was a considerable increase to the beginning of May (DAP 48). During May the covering was kept 100 % until the crop started maturity (DAP 84). In Fig. 6 the measured canopy cover (dots) and the simulated canopy cover is shown. AquaCrop model was able to simulate the progression of green canopy cover over the season.

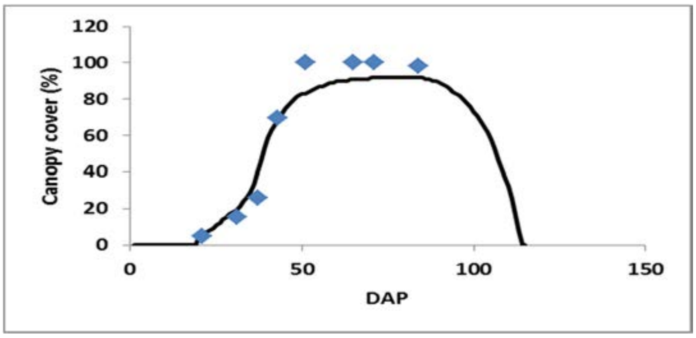


FIG. 6. Simulated as compared with measured canopy cover progression of spring barley.

Evaporation (from soil) occurred from planting during the period of germination and crop development until beginning of May (Fig. 7). With the beginning of May spring barley covered fully the soil and evaporation was reduced to zero. After the full maturation of barley little evaporation occurred again. It can be concluded that between May and mid-June crop water consumption goes directly into transpiration and no losses by evaporation appeared. AquaCrop calculated 323 mm transpiration and 37 mm evaporation over the vegetation period. From the total water use of 360 mm for spring barley at least more than 10 % could be saved if technically feasible. 37 mm are equivalent to 370 m³ per hectare–this shows the potential of water savings.

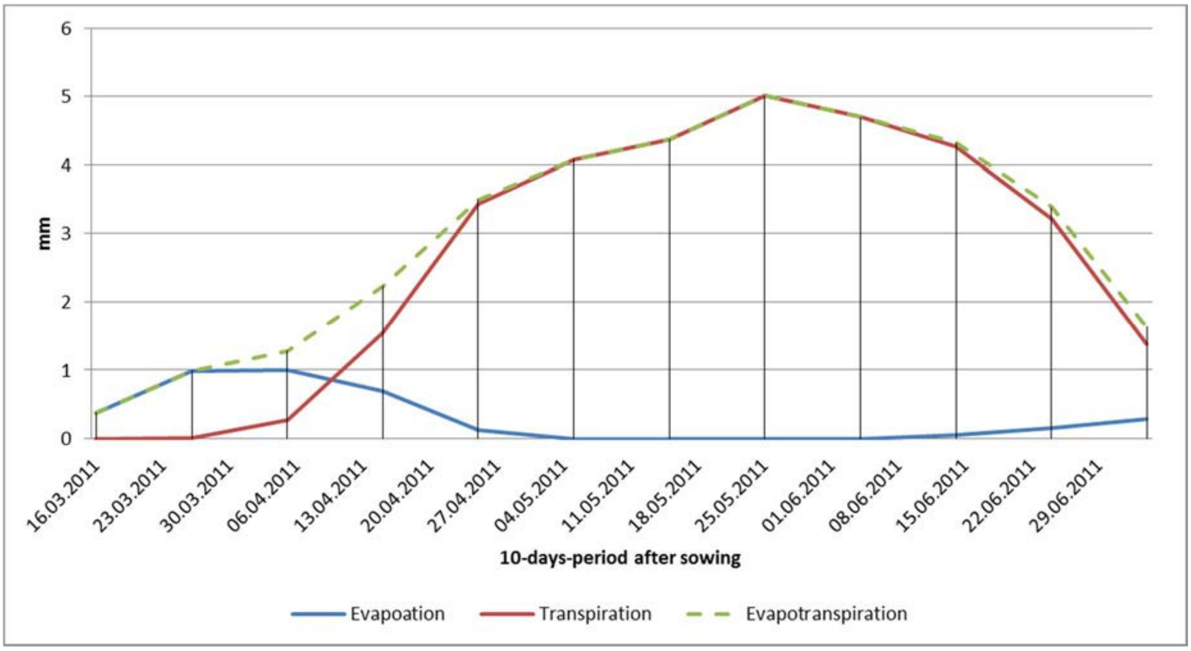


FIG. 7. Evaporation, transpiration and evapotranspiration in mm per day for the investigated spring barley determined by AquaCrop.

Using isotopic and modeling approaches the total evapotranspiration flux was partitioned into the E and T components [18]. The fairly realistic mimicking of the measured canopy cover showed the validity of using a conservative normalized water productivity value. From the simulation results, the transpiration component was observed to be close to 100 %, with minimal evaporation during the study period (25–27 May 2011). The estimated F_T ranged between 95.4–104 % which is similar to that simulated using AquaCrop model (100 %). The good agreement between the two contrasting approaches in predicting E and T components implies AquaCrop model which is a simple, easy to use model which requires relatively few input parameters is a valuable tool for estimating crop productivity under rain fed for devising on-farm water management strategies for improving the efficiency of water use in agriculture.

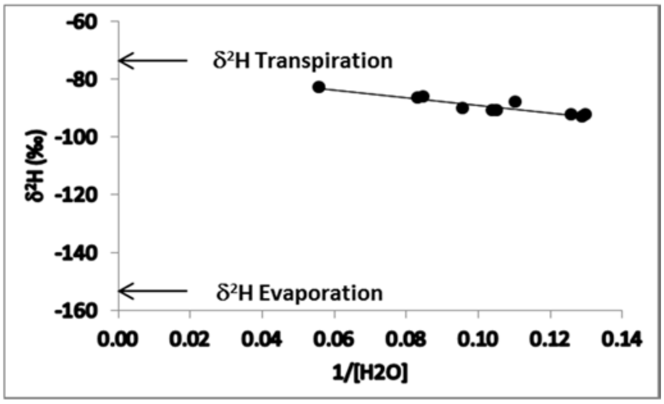


FIG. 8. Keeling plot of δ^2H of atmospheric water vapour collected at different heights above and within spring barley canopy plotted against the inverse of absolute humidity.

4. CONCLUSIONS

Weather conditions were rather dry during the study period. The characteristics of profile water content was similar in the upper soil layer from 0 to 80 cm soil depth in the lysimeter and in the field; however lysimeter measurements showed a decrease of soil water content also in deeper soil layers. Obviously, this was due to plant water uptake and soil water fluxes towards the main rooting zone, respectively. Since the soil water sensors in the field did not measure in this deeper zone, evapotranspiration of spring barley was very likely underestimated during the middle vegetative period.

The determination of canopy cover development by means of picture analysis provided a good basis for AquaCrop modeling, but the method itself was rather time consuming and labour-intensive. The model delivered proper results of daily evaporation and transpiration. The latter corresponded well with the isotopic analysis.

ACKNOWLEDGEMENTS

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ISOTOPIC AND CONVENTIONAL TECHNIQUES TO IMPROVE THE IRRIGATION PRACTICE FOR ENHANCING AGRICULTURE PRODUCTION UNDER WATER LIMITING CONDITIONS IN MOROCCO

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Abstract

The arid and semi-arid regions constitute roughly one third of the total earth's surface. In these regions water scarcity is one of the main limiting factors for economic growth. The impact of such water scarcity is amplified by inefficient irrigation practices, especially since about 85% of the available water is used for irrigation in these regions. Therefore, a sound and efficient irrigation practice is an important step for achieving sustainable management of water resources in these regions. In this regard, a better understanding of the water balance is essential to explore water-saving techniques. In the context of this CRP project, experimental setups were conceived to monitor seasonal water consumption on the wheat crop irrigated by flood irrigation in Sidi Rahal station (middle of morocco. The partitioning of evapotranspiration compounds shows that transpiration dominates the evaporation about 68 % for three days (22, 23 and 24 February 2012). In addition the wheat absorbs the soil water from 10 cm to 20 cm (90%) at this growing stage according to the multiple-source mass balance assessment.

1. INTRODUCTION

In Morocco, the arid and semi arid areas take up 27% of the surface and 87% of arable land, whose 60% is covered by cereal culture [1]. The cereal production remains insufficient to meet the country interior needs in this food product. To increase productivity by the improvement of the farming techniques is not only imperative, but it is the only solution to be considered. Enormous efforts were made to increase the yield. However the techniques used are limited by drought which affects this crop during all its vegetative cycle. The irrigation of cereals remains the only possible way to improve the production. According to the FAO estimation, about 40% of food products produced in the world is cultivated under irrigation, however a great quantities of water used for this purpose are lost through the irrigation systems. The irrational irrigation practices are one of the principal soil salinity causes. Approximately 10 percent of the irrigated surfaces in the world are degraded by salt. Also the climatic changes make more areas in the world exposed to both drought and desertification risks. The improved irrigation practices will contribute to preserving water and to protect the vulnerable soil. One widely used approach is conventional deficit irrigation (DI) but it requires crop-specific information for its effective use [2].

In the arid and semi arid areas, which suffers from water shortage due to the scarcity of rainfall and to the increasing demands of water under the demography pressure and agricultural activity effect, the evapotranspiration constitutes the most important factor of water loss, whose determination is important for a well-control water resources management.

Contrary to classic methods traditionally used, which remain insufficient (micro-lysimetry, sap flow) to determine correctly the evapotranspiration partition, the isotopic geochemical methods also provide better understanding the extraction water processes by roots. Indeed, the heavy stables isotopes content increases with soil evaporation. On the other hand, the water extraction by the roots does not have effect on this concentration. Water from growing-season precipitation is rapidly lost from the rooting zone by the transpiration or soil evaporation depending, in part, on the size of the precipitation event [3] and structural and physiological characteristics of the vegetation [4] the ratio of transpiration (T) to evapotranspiration (ET) is a synthetic parameter that integrates ecophysiological and microenvinronmental controls on total ecosystem water exchange [5].

Indeed, in an isotopic steady-state condition of leaf water, transpiration introduces into the atmosphere a vapour whose isotopic signature is identical to that of root water [6]. In a δ^2H-$\delta^{18}O$ diagram the signature of water vapour originally from transpiration belongs to the local meteoric water isotopic composition. The evaporation causes a little modification of isotopic composition of rainfall seepage in the surface layers of ground [7, 8]. Moreover, the roots system, which is often widely developed in these surface soil layers, allow, by evaporation the plant alimentation in a heavy isotope rich water. At last, the root extraction changes strongly the water distribution in different soil horizons and then the availability towards the vegetable covers. There are obviously a lot of consequences on the agronomic and hydrologic levels. The soil relative humidity, the hydraulic potential, the hydraulic conductivity, the root structure, the chemistry of soil solutions, and the evaporation - transpiration ratio are a parameters whose the determination is essential to understand the water transfer in soil-plant-atmosphere continuum.

In this regard, a better understanding of the water balance is essential for exploring water-saving techniques and to avoid the contamination of ground water. The most important components of water balance in semi-arid areas are the evapotranspiration and the deep percolation. Effective methods, such as lysimetric method, sap flow measurement techniques, and micrometeorological techniques are used to measure or estimate ET. But, there are several limitations in using these methods. Stable isotopic tracer methods offer a new opportunity to study the components of ET at the field-scale, from the leaf level to ecosystem, and can partition the ET from different compartments of the ecosystem incorporating measurement of water vapour.

2. MATERIALS AND METHODS

2.1. Study site

The study is conducted in experimental station, irrigated with flood irrigation system; the experiment took place in one of the irrigated areas, which has been managed since 1999 by a regional public agency (Office Régional de Mise en Valeur Agricole du Haouz (ORMVAH)). The fields are generally sown between 15th November and 15th January, and the harvest occurs after 5–6 months, in May or June. The station is located approximately 30 km southwest of Marrakech city, Morocco. This area has a semi-arid Mediterranean climate, characterized by low and irregular rainfall with an annual average of about 240 mm against a higher reference evapotranspiration (ET_0=1600 mm/year). The soils have high sand and low clay contents (18% clay, 32% silt, and 50% sand).

2.2. Meteorological data

The study site was equipped with a set of standard meteorological instruments to measure wind speed and direction (model Wp200, R.M. Young Co., Traverse City, MI, USA) and air temperature and humidity (model HMP45AC, Vaisala Oyj, Helsinki, Finland) at four heights. Net radiation over vegetation and soil was measured using net radiometers (a model CNR1, Kipp and Zonen, Delft, The Netherlands and the Q7 net radiometer (REBS Inc., WA, USA)). Soil heat flux was measured using soil heat flux plates (Hukseflux). Water content reflectometers (CS616, Campbell Scientific Ltd.) were installed at depths of 5, 10, 20, 30, 40, 60 and 80 cm in order to measure the soil humidity profile. Measurements were taken at 1 Hz, and averages stored at 30-min intervals on CR23X data loggers (Campbell Scientific Ltd.).

3. STABLE ISOTOPES MEASUREMENTS

3.1. Soil water, plant water and vapour sampling

Using a hand-auger, soil was sampled from the surface to 10 cm. Sampled branches of orange tree were 0.5~1.0 cm in diameter, 1~2 cm in length and from each of them the bark was removed. Every plant sample was composed of 2~3 stems from different individuals. Soil and plant samples were placed into screw-cap glass vials (5 ml) and sealed with Parafilm, then stored at about 2°C. Soil and plant water was extracted by cryogenic vacuum distillation [10].

Water vapour was collected from 4 heights at the same time. During the collection period mentioned above, sampling was started at 10:00, 11:00, 13:00, 14:00 and 15:00 h. For each group, vapour was collected during 1 hour with a flow rate of 250 ml/min using a vacuum pump. The air was circulated through a set of 45 cm long glass traps [11] which were immersed in a mixture of ethanol and liquid nitrogen (about -80°C). Traps were made of 9 mm diameter Pyrex glass attached to 6~9 mm diameter Cajon Ultra-Torr adapters which framed in 9 mm diameter Swagelok Union Tee. After sampling the traps were sealed with Parafilm and stored at about 2°C.

Near the vapour sampling inlets, probes of model HMP45AC, Vaisala Oyj, Helsinki, Finland for measuring the air temperature (T_a, in Kelvin) and relative humidity (h,) every 5 min. Using T_a, h and atmospheric pressure (Pa, in hPa), water vapour concentration (mmolmol^{-1}) was calculated by [12]: Eq. 1

$$H_2O = 10h\left[P_a \exp(13.3185t - 1.9760t^2 - 0.6445t^3 - 0.1299t^4)\right] / P_a \qquad (1)$$

where P_a is standard atmosphere pressure (about 1013.25 hP_a) and t = 1 (373.15/T_a).

3.2. Stable isotope and data analysis

In the laboratory soil and plant water was extracted by cryogenic vacuum distillation [10]. The water samples were isotopically analyzed at National Center of Sciences and Nuclear Techniques by laser spectrometer DLT-100 (±1 standard deviation). The standard deviation for repeated analysis of laboratory standards was 0.2‰ for ^{18}O and 1‰ for D. Concentrations of these isotopes are expressed as deviation from an international standard (V-SMOW) and using δ notation in per mil (‰): Eq. 2.

$$\delta‰ = [(Rs / Rst) - 1] * 1000 \tag{2}$$

where Rs and Rst are the molar ratio of the heavy to light isotopes in the sample and the standard, respectively.

3.3. Theoretical overview

The isotopic ratio of the atmospheric water vapour at a certain altitude can be described using Eq. 3 by considering mixing of evapotranspired water vapour and free atmospheric water vapour [13, 14]. This relationship is linear, and when used with water vapour the y-intercept reflects the source isotopic composition of the evapotranspiration flux:

$$\delta_{ebl} = C_a(\delta_a - \delta_{ET})\frac{1}{C_{ebl}} + \delta_{ET} \tag{3}$$

where δ_{ebl} is the isotopic composition of vapour collected from the ecosystem boundary layer, C_a the atmospheric vapor concentration, C_{ebl} the vapour concentration in the ecosystem boundary layer, δ_a is the isotopic composition of the atmospheric background and δ_{ET} indicates the isotopic composition of the evapotranspiration flux. The Keeling plot approach is based on the assumption that the atmospheric concentration of vapour in an ecosystem combines the inputs of two major sources: the background vapour from the atmosphere and vapour added by the sources in the ecosystem. It is further assumed that the only loss of water vapor from the ecosystem is by turbulent mixing with the background atmosphere.

The isotopic ratio of evaporated water vapor from the soil surface is described below by considering the fractionation process [15] in Eq. 4:

$$\delta_E = \frac{\alpha * \delta_{surf} - h\delta_{atm} - \varepsilon_{eq} - (1-h)\varepsilon_k}{(1-h) + (1-h)\varepsilon_k {}^{\varepsilon_k}\!/_{1000}} \tag{4}$$

δ_E: is the isotopic composition of soil evaporation flux
α*: is the temperature dependent equilibrium fractionation factor
ε_k: is the kinetic fractionation factor
h: is the relative humidity normalized to the temperature at the evaporation surface in the soil
δ_{atm}: is the isotopic composition of atmospheric vapour
$\delta_{surface}$: is the isotopic composition of water at the evaporation surface in the soil.
The best equations describing α* are those provided by Majoube [16] Eq. 5

$$^{18}O\alpha * = [1.137(10^6 T^2) - 0.4156(10^3 T) - 2.0667] / 1000 + 1 \tag{5}$$

$$D\alpha^* = [24.844(10^6 T^2) - 76.248(10^3 T) - 52.612]/1000 + 1 \qquad (6)$$

where T is soil temperature recorded at 5 cm depth in degrees Kelvin.
ε_k is estimated using the diffusivity ratios of 1.0251 for H_2O: HDO and 1.0281 for H_2O:$H_2{}^{18}O$ [17].

The contribution of transpiration to evapotranspiration is estimated by Eq. 7 [18]:

$$F_T = \frac{\delta_{ET} - \delta_E}{\delta_T - \delta_E} \qquad (7)$$

4. RESULTS AND DISCUSSION

4.1. Evolution of climatic conditions

The temporal evolution of ET_0 is typically of a semi arid continental climate type. It is characterised by a high climatic demand. The lowest values of ET_0 (0.99 mm/day) occurred during the winter and highest values occurred in the summer (9.89 mm/day) in this figure the evolution of ET_0 is similar to Tmean of air. Precipitation temporal patterns over the growing season of citrus trees were characterized by low and irregular rainfall events, with a total precipitation amount of about 295 mm. The amount and timing of irrigations applied by the farmer are presented (Fig. 1)

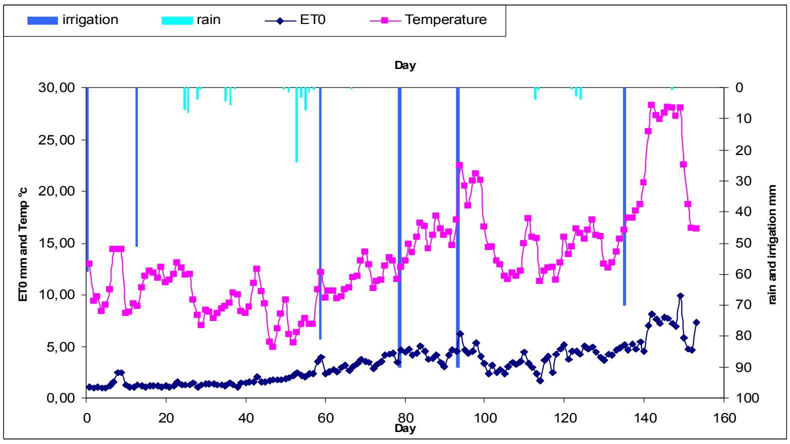

FIG. 1. The environmental condition during the growing season.

4.2. Partitioning evapotranspiration components

4.2.1. The stable isotopic composition of vapour water, soil water and irrigation water

The following figure (Fig. 2) chows that the continent of all samples for the three days of sampling (water vapour, soil water, irrigation water) are situated around the LMWL. The regression line of the all samples intersects the LMWL at point that present the origin of all the samples. The vapour profiles (Fig. 3) represent an isotopic heterogeneity during the three days, it gradually impoverishment -71.96‰ to -87.01‰. However the vertical variation of δD shows a homogenization in vegetation since 14:00 and it come on totality homogenization around 16:00. That shows the high contribution of vegetation in hydrology cycle.

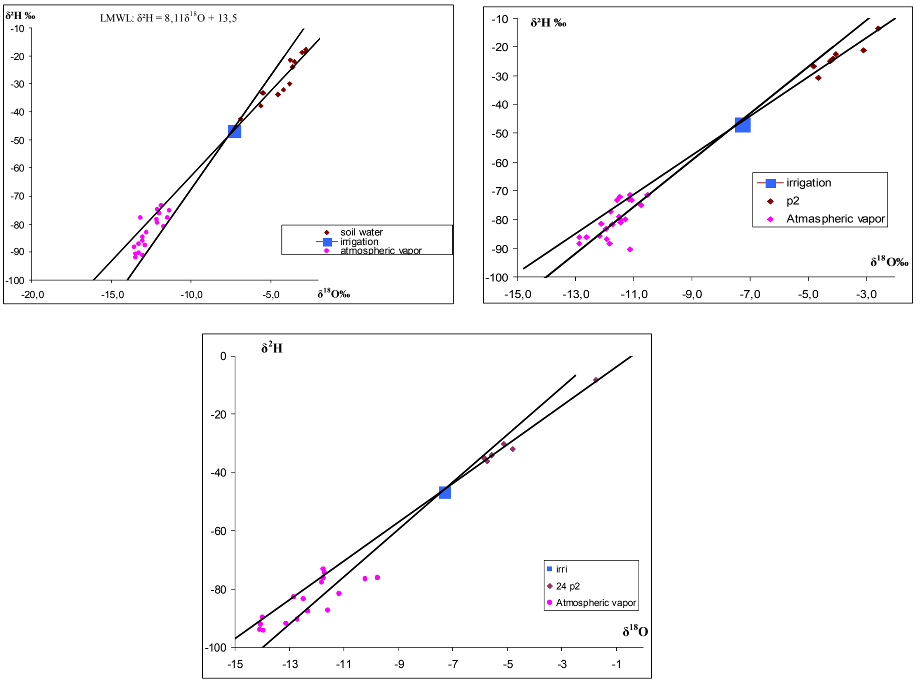

FIG. 2. $\delta^{18}O$ versus δD in atmospheric water vapour, irrigation and soil water observed at wheat study case (A 22nd, B 23rd and C 24th February).

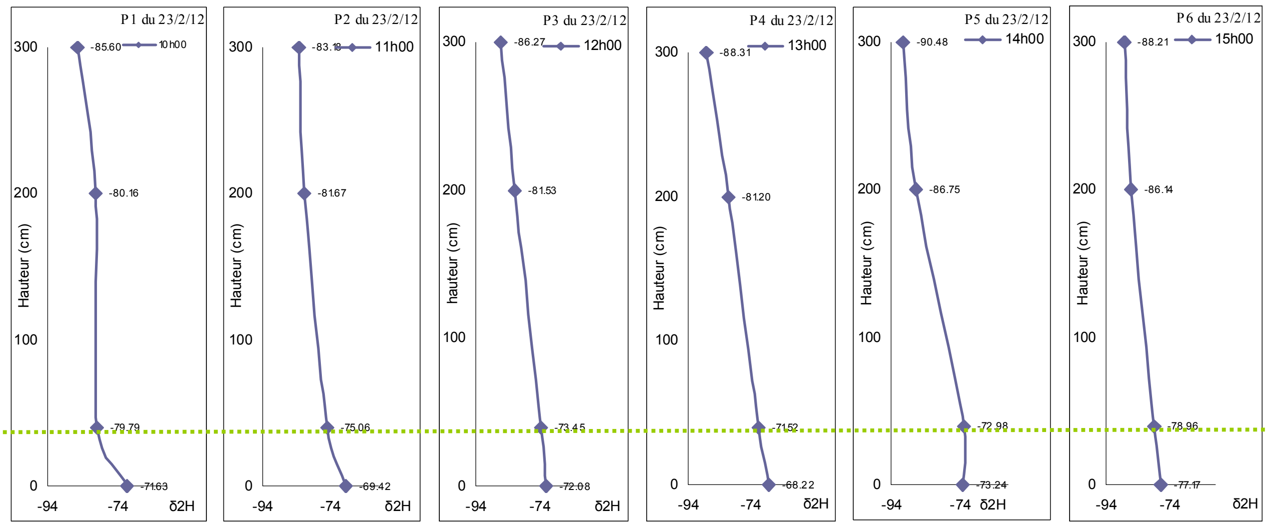

FIG. 3. Evolution of isotopic composition (δD) of atmospheric vapour at different levels in and out vegetation (B 23rd February 2012).

4.2.2. Keeling plot analysis

A significant regression lines were found in Keeling plot pictured by δD, although those plotted by $\delta^{18}O$ were not significant. Table 1 shows the different slopes and the intercepts of keeling plots. All the intercepts of Keeling plots (Fig. 4) were close to symbols which reflected isotopic values of plant transpiration relative to that reflected isotopic compositions of soil evaporation. This meant plant transpiration contributes more to ET than soil evaporation. Considering wheat transpiration as one source and the soil evaporation as another one, the fractional contributions of plant transpiration to total ET (T/ET) were 73%, 59% and 74% for δD on 22nd, 23rd and 24th February, respectively. This may be explained by height canopy cover, about 77% at this growing stage (maturation). The maturation period had larger E/ET ratios because of the smaller LAI and more bare area with low transpiration [19].

Yucui Zhang [20] combined isotopic and micrometeorologic approach to investigate the responses of transpiration and soil evaporation to an irrigation event in an winter wheat field, and the results show that transpiration was 4.91 mm, or 83% of total ET on DOY138 and 1.02 mm, or 60% of ET, on DOY149.The higher percentage transpiration during the filling stage is expected because this stage corresponds to a higher LAI and increasing biomass.

Liu et al. [19] found that transpiration took up 70.3 and 69.7% of the total evapotranspiration for irrigated winter wheat and summer corn field in the growing season, respectively, at Luancheng Station in the North China Plain, based on the measurement of large-scale weighing lysimeter and two micro-lysimeters. These research conclusions about T/ET in irrigated field are similar to our results in this study, so the method of Linear mixing with atmospheric vapour (Keeling plots) to partition the evaporation and transpiration in study area is credible.

However, for the researches not related to irrigation, the partitioning results have some difference. The T/ET ratio is relatively low for plants under semi-arid or arid climate [21, 22], and relatively high under humid climate, which has similar moisture conditions as after irrigation. Hsieh [23] studied the T/ET in soils along an arid to humid transect in Hawaii by oxygen-18, and the T/ET ratio increased from 14% to 71%.

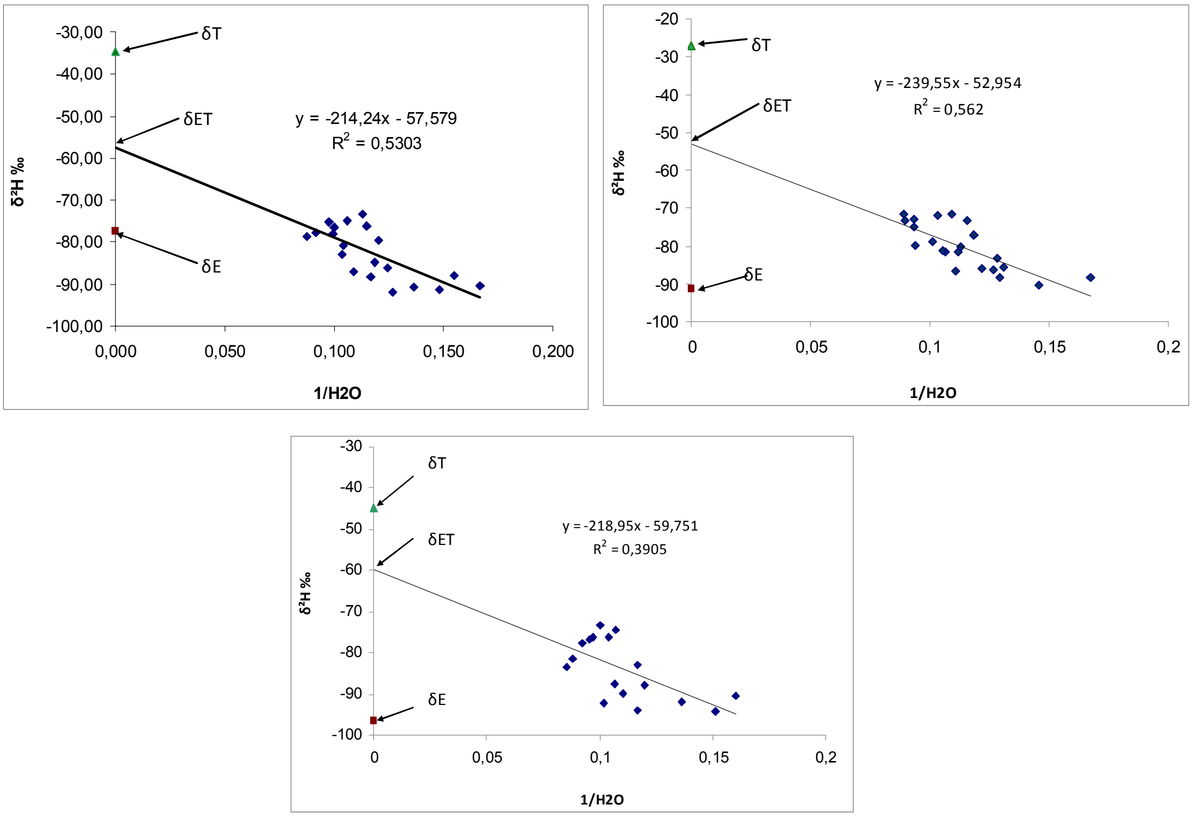

FIG. 4. Relationship between δD and the inverse of the air absolute humidity at different levels above the ground (A 22nd, B 23rd and C 24th February).

TABLE 1. SLOPE AND INTERCEPT OF THE REGRESSION LINES BETWEEN ΔD VALUES OF WATER VAPOUR COLLECTED AT DIFFERENT HEIGHTS AND THE INVERSE OF THE CORRESPONDING VAPOUR CONCENTRATION. THE INTERCEPT INDICATES THE ISOTOPIC VALUES OF EVAPOTRANSPIRATION (δET)

	δs	δa	δT	δET	P	R^2	α	εk	δE	FT%
22/02/12	-27.26	-73.46	-34.55	-57.58	0.0002**	0.530	1.08	1.03	-119.28	0.73
23/02/12	-5.72	-68.22	-27.29	-52.95	0.0001*	0.562	1.08	1.03	-90.09	0.59
24/02/12	-26.05	-71.36	-37.44	-59.75	0.002*	0.39	1.08	1.03	-122.06	0.74

*The significance level is 0.05.

4.3. Root water uptake depths

For the soil and stem water sampled at the same time, according to the mass balance of soil water and its isotopes, the proportions of each layer (f1–f4) can be determined by their isotopic signature and the isotopic signature of mixture (stem water) (Eq. 8)

$$\delta Xt = f1\delta X1 + f2\delta X2 + f3\delta X3 + f4\delta X4 \quad (8)$$

with: $1 = f1 + f2 + f3 + f4$

IsoSource [24] was used to evaluate the relative contribution of each soil layer to stem water. The fractional increment was set at 1%, and the uncertainty level was set at 0.2.

The multiple-source mass balance assessment shows that the wheat absorbs the soil water from 10 cm to 20 cm (90%) at this growing stage (Fig. 5A). Fig. 5B shows hydrogen isotope in the soil profile and corresponding crop stem. The isotopic profiles of soil water are determined by the evaporation effect and the antecedent precipitation and irrigation. Because soil was sampled when there was no rainfall several days before, the surface soil water was isotopically enriched due to evaporation. For other soil water, the isotopes were a mixture of evaporation effect and the isotopic signatures of antecedent precipitation and irrigation event.

In direct inference approach, the intersection of stem water isotopes 'vertical line and the soil water isotopes 'profile is considered to be the main depth of root water uptake. According to this direct inference we can get: the main depths of root water uptake of winter wheat are between 10 and 20 cm in this growing stage.

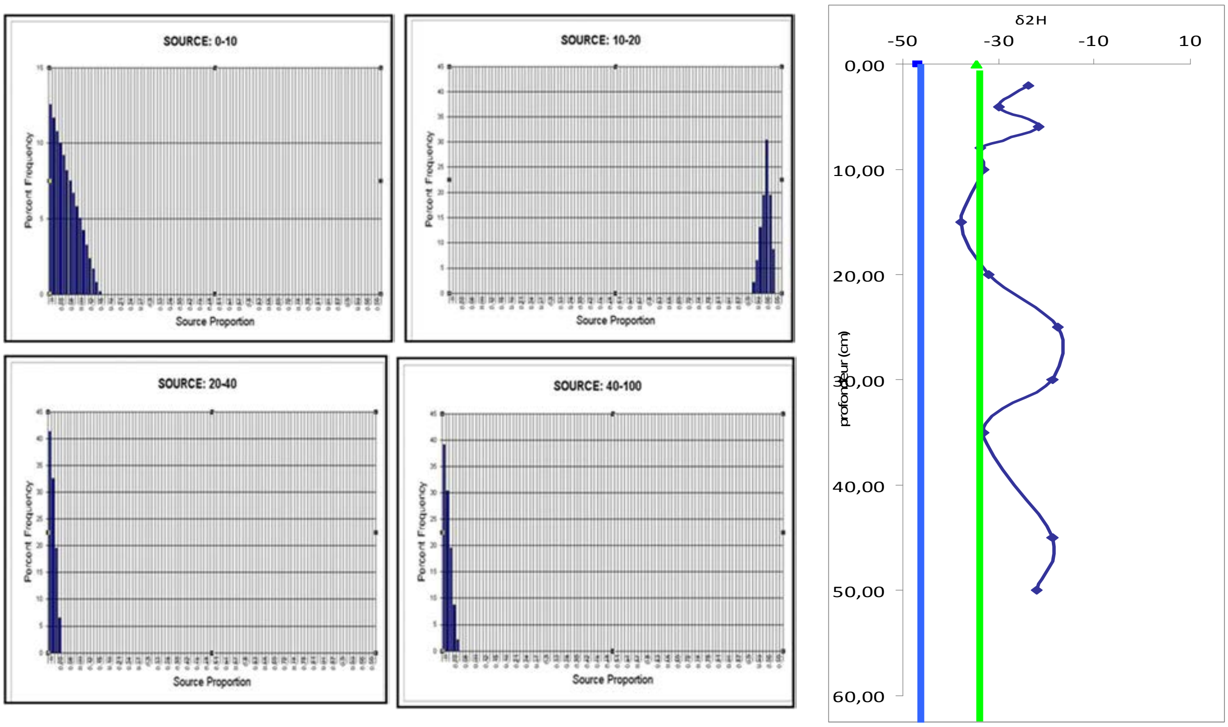

FIG 5. Histograms obtained by the multi-source mass balance, which show the estimated ranges of proportional contribution of water from each soil depth to total water uptake of winter wheat (green line stem water, bleu line irrigation water).

5. CONCLUSIONS

This study, shows that the Keeling plot technique give a good result for the partitioning of evapotranspiration components with high R^2. The direct comparison shows: the main depth water uptake of winter wheat is 10 cm in this growing stage. The multiple-source mass balance assessment give the same result that direct approach, this one shows that the wheat absorbs the soil water from 10 cm to 20 cm (90%) at this growing stage.

The present project constitutes an appropriate complement of previous attempts to quantify evaporation in irrigated areas within selected sites including different type of irrigation practices and different kind of vegetation (culture) and. This conclusion is useful for agricultural water management and irrigation schedules.

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WATER USE EFFICIENCY OF COFFEE (ROBUSTA) UNDER MULCH AND DRIP IRRIGATIONON AT THE TAY NGUYEN PLATEAU, VIET NAM

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Abstract

Comparison of the irrigation water use efficiency (WUE) of coffee (Robusta) crop under furrow and drip irrigation practices, with and without mulching was presented. The experiments were conducted in a ten-year old coffee plantation on a clay soil in the Tay Nguyen plateau, in the Central Part of Viet Nam. The plantation was relatively homogeneous in terms of crop height, with a leaf area index (LAI) ranging from 6 to 7. The study showed that the transpiration of the coffee trees was the highest (95±5% of the total evapotranspiration, ET) during the flowering stage (Feb–Mar), but was lowest (47±3% of the ET) during the maturing and canopy reforming stage (Oct–Nov), as separated by isotopic technique using the Keeling plot approach. Drip irrigation (DI) combined with plant residues mulching increased the WUE of coffee up to 2.13 kg clean bean per cubic meter of irrigated water (kg/m^3) while WUE under DI and furrow irrigation (FI) without mulch was only 1.75 and 1.11 kg/m^3, respectively. Due to the WUE improvement the local farmers could be profitable from the application of DI with mulching practice to their coffee crop. DI with mulch by plant residues is advised to the local farmers to apply for all coffee plantations at the Tay Nguyen plateau.

1. INTRODUCTION

Water is needed for plants to produce biomass. The role of water in getting high crop yield was recognized by every farmer worldwide. In Viet Nam, wherever water is abundant farmers usually irrigate excessively to their crops without thinking the negative effects of over-irrigation, which can result in run off fertilizers to surface water body causing eutrophication or leaching of agrochemicals into deep aquifers contaminating groundwater. On the other hand, wherever water is scare during the dry season, farmers do not apply any measure to maintain or conserve soil moisture. The concept of water use efficiency (WUE) is still not familiarized to Vietnamese farmers.

In irrigation engineering, good WUE is understood as the highest crop yield with a minimum amount of irrigated water. A good WUE could be achieved by the application of several approaches, e.g. deficit irrigation method [1] [2], covering the soil with plant residues or mulching technique [3][4]. All these techniques are, in fact, aimed at to minimize the evaporation (E) while maximize the transpiration (T) component in the total evapotranspiration (ET) of plants. It is therefore important to know the contribution of the E and/or T component in the evapotranspiration (ET) of a crop to develop technological approaches to improve its WUE. This is particularly important in areas of scare water resources.

Currently, Viet Nam is the second biggest coffee exporter in the world. In 2011, 1.2 million tons of clean coffee bean has been exported which is equivalent to US $ 2.7 billion on the London coffee market [5]. Coffee crop is cultivated mainly on clay soil in the Tay Nguyen plateau, Central Part of Viet Nam, at an elevation of 600–650 m a.s.l., with a total area of 290 000 ha. Average air temperature in the year is 23±7°C and rainfall is 2,000±120 mm but not evenly distributed over the year [6]. For the last decades there is increasing variability of the climate in the country, extreme events, e.g. rain was heavier in the rainy season, typhoons from the Pacific Ocean hit the land with unusual trajectories compared to those in the past, and were more frequently observed [7]. Rainfall at the Tay Nguyen plateau, during the rainy season (Apr–Aug) is usually heavy, but during the dry season (Sep–Mar) there is almost no rain. In fact, the recent dry spell was so severe in the main coffee-growing area in the Central Highlands that it is affecting the growth and supply of robusta beans. This requires farmers to irrigate their coffee crop for the period from September to the next March. The irrigation practice that the local farmers has been using was furrow irrigation (FI) with low WUE, causing losses of soil and nutrition due to the erosion and percolation of the nutrient into deeper soil profile, threatening the deterioration of groundwater quality.

The aim of this study was to investigate the cultivation practices that could improve WUE of coffee plants, i.e. to maximize T while minimize E of the crop. The investigation consists of the following: i) separation of E and T from the total ET of the crop using isotopic technique for coffee trees at different stages of its development cycle: maturing, bean development, bean formation, flowering, and buds development stage; ii) compare the WUE of coffee plants under DI with mulch and that under the traditional FI without mulch. The first study was essentially to evaluate at what stage in the coffee development cycle the crop needs water most, i.e. the T component is the highest that needs to irrigate. The second study aims to show the advantage of the DI with scheduling in combination with mulch (DIS&M) over the traditional furrow irrigation and no mulch (FI) practice. It hopes that the cooperation with the local farmers in conducting this investigation would be the best way to prove a fact that application of advanced agronomic practices could improve the WUE of their coffee crop that directly lead to the increase of their profit.

To our knowledge this is the first time that an investigation on E and T separation, WUE and agronomic practices that could improve WUE of coffee plants was conducted in Viet Nam.

2. EXPERIMENTAL

2.1. Location

The experiment was conducted in a coffee plantation located in the Dak Ha town of Dak Ha district, Kon Tum province (14°32’329N, 107°56’893E) at an elevation of 2080 ft (630±20 m a.s.l.). The coffee plantation occupies an area more than 100 ha and it belongs to several farmers. The coffee is Robusta var. planted on clay soil by rows of 3 x 3 m. The crop is of 10 years old which is just at the productive age. The trees were treated in such a way so that its canopy is just inter-covering each other. The leaf area index (LAI) of the trees was between 6 and 7. Water used for irrigation to the crop was taken from a canal originating from a lake located around 2 km from the plantation. The canal passes under the foot of the hill of the coffee plantation. Fig. 1 shows a view of the coffee plantation where the study was conducted.

FIG. 1. A view of the coffee plantation (in April) where the study was conducted.

2.2. Methods

In this study the Keeling method [8][9] was applied to separate E and T from the total ET of coffee trees. The Keeling method was based on the assumption that the uptake of water by plant roots occurs without isotope fractionation so that the isotopic composition of the atmospheric moisture above the canopy would be different from that of the moisture within the canopy and from the evapotranspiration sources. The isotopic mass balance of each component could be given as [10]:

$$\delta_{under} = C_{above}(\delta_{above} - \delta_{ET})\frac{1}{C_{under}} + \delta_{ET} \qquad (1)$$

where δ_{under}, δ_{above}, and δ_{ET} denotes the isotopic composition of either deuterium (^2H) or oxygen-18 (^{18}O) in ‰ in the air moisture under, above the canopy, and in the atmospheric moisture or evapotraspiration, respectively. C_{under} and C_{above} denote the moisture content under and above canopy layers, in mMol m^{-3}, respectively.

If the content of moisture within the canopy (C_{under}) and its isotopic composition, e.g. of ^{18}O (δ_{under}) is known then one could construct a graph of δ_{under} vs. $1/C_{under}$, which is known as the 'Keeling plot'. From the Keeling plot, the value of δ_{ET} could be derived as the intercept of the graph, and the contribution of T component (F_T) to the total ET can be calculated as:

$$F_T = \frac{\delta_{ET} - \delta_E}{\delta_T - \delta_E} \qquad (2)$$

where δ_E and δ_T denote the isotopic composition of soil evaporation and plant transpiration, respectively.

The values of δ_E and δ_T were, respectively, the isotopic compositions of (^{18}O or ^2H) in soil water within the rooting zone and moisture of plant tissue. In this case plant tissues are the skin of the secondary branches of the coffee trees.

The atmospheric moisture along the canopy was collected using cryogenic traps following its isotopic composition (δ^2H and $\delta^{18}O$) analysis in the Laboratory of the Isotopes Hydrology, Institute for Nuclear Sciences and Technologies (INST) in Ha Noi. The air moisture content along the coffee canopy (C_{under}, kg/m^3) was determined using a psychometric device that was designed and constructed by engineers of the INST. Details of the device are described below, under Section 2.3.

In the experiment with mulch, the farmer was instructed to leave on the land all the branches and leaves after the canopy reforming stage, but not clean up as he used to do previously. The thickness of the mulch was 5–8 cm. Fig. 2 shows pictures of coffee plants under mulch and without mulch, respectively.

FIG. 2. Pictures showing coffee plants under mulch with the plant residues (left) and without mulch (right).

Scheduling in the drip irrigation was set up based on the assumption that the plant needs to be watered when the refill point (RP) was down to half of the available soil water content (ASWC):

$$RP = 0.5 * ASWC \qquad (3)$$

and ASWC is estimated as:

$$ASWC = FC - WP \qquad (4)$$

where FC is the field capacity and WP is the wilting point.

For a clay soil, the ASWC was recommended as high as from 10 to 20% [11]. The FC and WP of clay soil in the coffee plantation under this study was 27% and 7%, respectively, as determined experimentally. So, the ASWC of the soil would be as high as 20% (Eq. 4) and the crop needs to be watered when the moisture within its rooting zone was down to 10% (Eq. 3). The rooting zone of coffee plants was suggested to be 2 000 mm, i.e. RTZ = 2 000 mm.

The amount of irrigation water in the drip irrigation with scheduling (DI&S) was estimated for each watering time so that it was watered just enough to reach the FC. In the FI the plot was left to the farmer to manage the timing and amount of water for watering as he did previously. Fertilizers used as well as the fertilization rate for the crop in the experiment were managed by the farmer himself also.

The soil moisture in this study was measured and monitored by using a neutron probe (PB-205, FIELDTECH, Japan). To compare WUE of coffee crop under the improved management practice i.e. DI&M, with those under the FI, an experiment was conducted for three years 2009–2011. For each year, the total amount of irrigated water, I (m^3/ha), in both practices was recorded using water meters. The yield (Y) of the crop (kg/ha) harvested in each harvesting season after processing to bean and air dry was recorded also. The irrigation WUE [12] was calculated as:

$$\mathrm{WUE} = \frac{\mathrm{Y}}{\mathrm{I}}\ (\mathrm{kg/m^3}) \qquad (5)$$

2.3. Instruments

2.3.1. Air temperature measurement and estimate of the atmospheric moisture content

In order to estimate the atmospheric moisture, a ‘multi temperature’ device was designed and assembled by engineers of the INST. As the height of the coffee trees was 2.2–2.5 m, the device was constructed with 12 chromel/alumel thermocouples to install at six positions along the canopy. It was at ground layer 0 cm, 20 cm, 60 cm, 120 cm, 170 cm and 280 cm above the ground. The thermocouples were installed in pair, i.e. at each sampling position one sensor measured ‘dry’ but another measured ‘wet’ temperature. The wet bulbs were mounted with a piece of material immersed in a cup of water. This device functions like a traditional psychrometer used to determine the air humidity in meteorological observations. The device allows the record of both ‘dry’ and ‘wet’ temperatures continuously and at whatever time period, e.g. 30 seconds or 1 minute interval, as decided by the user. To do so, the thermocouples were connected to an electronic circuit to record the electrical signals appear at the junction. A software was installed in a computer to convert the electrical signals into temperature in degree Celsius (^oC). The device was calibrated in the Heat & Pressure Laboratory, Viet Nam National Metrological Institute and the accuracy of measured temperature was $\pm 0.1^oC$ in the range of 15–40^oC. Fig. 3 depicts the device connected to a set of 12 chromel/alumel thermocouples and computer on which the operational software was installed.

FIG. 3. ‘Multi-temperature’ device constructed by the INST’s engineers which functions like a psychometer used for determination of the air humidity in meteorological observations.

The estimate of the atmospheric moisture at each sampling position was made based on the ‘dry’ and ‘wet’ temperature using the Calculator for the properties of moist air program that available on the http://www.natmus.dk/cons/tp/atmcalc/atmocalc.htp [13]. Once the program is opened, if the ‘dry’ and ‘wet’ air temperature was entered in the right windows then tab away from the entry, all other values such as ‘Dew point’, RH, ‘moisture content’ in the unit of kg per m^3 or kg per kg air, ‘vapor pressure’ and ‘saturated vapor pressure, svp’ would appear. In the case shown if the ‘dry’ temperature of 39.5^oC and ‘wet’ temperature of

28.2°C was entered, respectively, in the windows of 'Air temperature' and 'Wet temperature' then tab away, the program would automatically calculate the rest of the air properties. The 'Dewpoint', 'RH', 'Air moisture', 'Vapour pressure' and 'svp' under the condition of dry and wet bulbs of 39.5 and 28.2°C would appear as 24.4°C, 43%, 0.021097 kg/m^3 equivalent to 0.01926 kg/kg, 3044 Pa and 7117 Pa in respective windows. The air moisture of 0.021097 kg/m^3 or 21.097 mg/m^3 will be then converted into the unit of mMol/m^3 by division to the molecular weight of water of 18 mg/mMol to construct the Keeling plot (Eq. 1) when isotopic composition of moisture collected at different heights of the coffee canopy was known from the mass spectrometric analysis described below.

2.3.2. Collection of the local meteorological data

The local meteorological data during the time of the experiment was recorded by a mini weather station, Vantage Pro2, supplied by the Davis Inst. Co. (California, USA). The device can record and create graphs of the air temperature (°C), relative air humidity (%), solar radiation (W/m^2), dew point (°C), wind direction, wind speed (m/min), rain rate (mm/h) and total daily rain (mm), atmospheric pressure (mb), potential evapotranspiration, ET_0 (mm) and etc.

2.3.3. Atmospheric moisture collection

The atmospheric moisture at five positions along the coffee canopy, at 20, 60, 120, 180, and 280 cm above the ground, was collected using cryogenic traps. The cooling agent used was liquid nitrogen stored in Dewars covered by a polyurethane foam covers through which glass tubes (traps) were punctured and positioned in the center of the Dewar. Fig. 4 depicts a scheme of the cryogenic traps system used for the atmospheric moisture collection.

The atmospheric moisture from the five sampling positions along the coffee canopy condensated in the bottom of the glass tubes (Fig. 4) was then transferred into vials of 1 ml capacity and tightly capped to avoid the evaporation during the storage in the field. These water samples were subject to the isotopic composition analysis in the laboratory in Ha Noi.

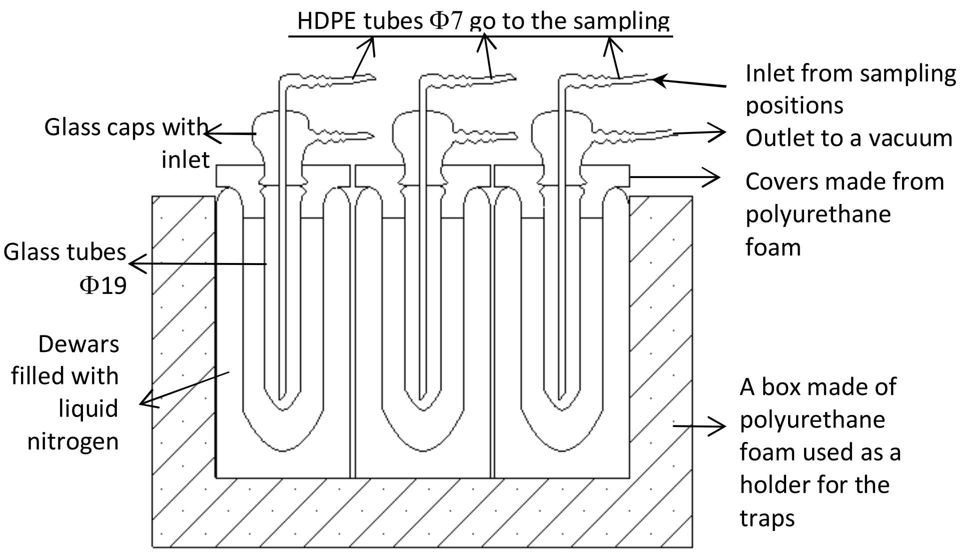

FIG. 4. A scheme showing a cryogenic traps system consisting of five traps (three were shown) used to collect the atmospheric moisture along the coffee canopy at 20, 60, 120, 180 and 280 cm above the ground.

2.3.4. Sampling soil and skin of coffee trees

Soil at a depth of 20 cm below the surface was collected using a metallic spool and stored in a vial of 10 g capacity. The vials were tightly capped to avoid moisture evaporation leading to the water isotopic fractionation. The samples were transported to the laboratory to extract the moisture.

The skin of the secondary branches of the coffee plants was slightly scraped off the dead tissue outside; it was then removed from the wooden part of the tree using a knife. Total weight of the skin samples was around 2–3 g in order to get 0.5–1.0 ml of water from it.

2.3.5. Extraction of moisture from soil and coffee tree skin

Moisture from soil and coffee tree skin was extracted using cryogenic trapping technique. The device used was shown in Fig. 5. It consists of series of round bottom glass flasks (Pyrex) into which soil or tree skin samples should be put for further extraction. The flasks were connected to the respective traps through its inlet and its outlet was connected to a vacuum pump. The traps were inserted into Dewars to cool in a mixture of propane alcohol and liquid nitrogen at –80°C. The set-up was connected to a vacuum pump to exhaust the air moisture inside before heating the flasks and cooling the traps. The pumping was ceased when the pressure in the system down to 25 mb by closing the two-ways valve connecting to the pump. Afterward, the heaters were turn on and maintained the temperature at 100±5 °C, meantime the traps were cooled down. The time needed for the moisture to be completely extracted from soil and plant tissues was four hours as it was checked with parallel drying a part of the same samples overnight.

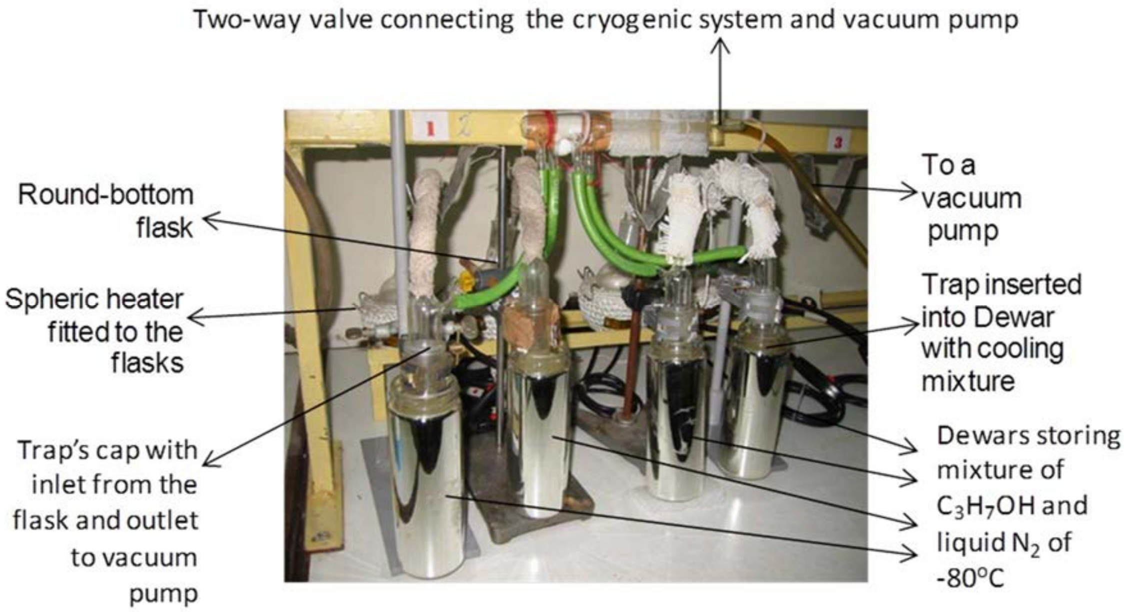

FIG. 5. Cryodistillation line used to extract moisture from soil and plant tissues for following isotopic composition analysis.

2.3.6. Analysis for isotopic composition of water samples collected

All the water samples collected (air moisture, soil moisture and moisture from the plant tissues) were analyzed for their isotopic composition, i.e. δ^2H and $\delta^{18}O$ using an IR MS supplied by the GV Instruments (UK). The facility was equipped with an Elemental Analyzer (Eurovector, Italy) capable of pyrolysis of water into either hydrogen on the nickel catalyst or carbon monoxide (CO) on glassy carbon, respectively, for the δ^2H or $\delta^{18}O$ analysis. The precision of the analysis was ±2.0 and ±0.2‰ for δ^2H and $\delta^{18}O$, respectively. Because of the precision of the $\delta^{18}O$ was better than those of the δ^2H, in this study the data of $\delta^{18}O$ were used to construct the 'Keeling' graph.

The accuracy of the analytical data was verified using VSMOW standards of IAEA. Additionally, the δ^2H and $\delta^{18}O$ in moisture collected by trapping and that measured directly in the field using a Picarro IR MS were in good agreement to each other as it was shown in Table 1, where the deviation between the two measurements was less than 5%.

TABLE 1. COMPARISON OF THE □^{18}O AND □^{2}H IN THE AIR MOISTURE COLLECTED BY THE TRAPPING TECHNIQUE FOLLOWED BY THE MEASUREMENT IN THE HA NOI LABORATORY TO THOSE MEASURED DIRECTLY IN THE FIELD BY A PICARRO INSTRUMENT

Comparison date	Height above ground (cm)	Data from Ha Noi Laboratory		Data from a Picarro instrument	
		$\delta^{18}O$, ‰	δ^2H, ‰	$\delta^{18}O$, ‰	δ^2H, ‰
23-Jun-09	20	–21.21	–92.17	–21.14	–92.58
(Corn field, Beijing, China)	50	–23.08	–94.23	–23.18	–93.90
8-Dec-10	10	–5.38	–32.40	–5.17	–32.20
(Soybean field, Ha Noi, Viet Nam)	40	–6.52	–41.40	–6.42	–41.71

3. RESULTS AND DISCUSSIONS

3.1. Variation of air moisture along the coffee canopy with time

Fig. 6 depicts the variation of the air moisture along the coffee canopy with time recorded in the bean development stage (April). It was observed that from 8:30 till 13:00 the content of the air moisture at the height of 60 cm above the ground was the highest (27–29 mg/m^3) but that at the height of 280 cm was the lowest (20–21 mg/m^3). Generally, the air under canopy was moister than that above the canopy (Fig. 6). This might be due to the photosynthesis process occuring mainly during the morning and noon time leading to the release of water, i.e. plant was transpiring water into the air making the air moisture under the canopy to be higher than that above the canopy. However, it seems that after 15:00 the stomata of coffee plants tend to close so that the transpiration became lesser and as a result the moisture content in both air layers, under and above the canopy tended to be closer to each other ranging from 19 to 21 mg/m^3. This finding implies that in the morning the plant needs more water for its transpiration activity and that if supplement irrigation were needed, it is better to irrigate in the morning.

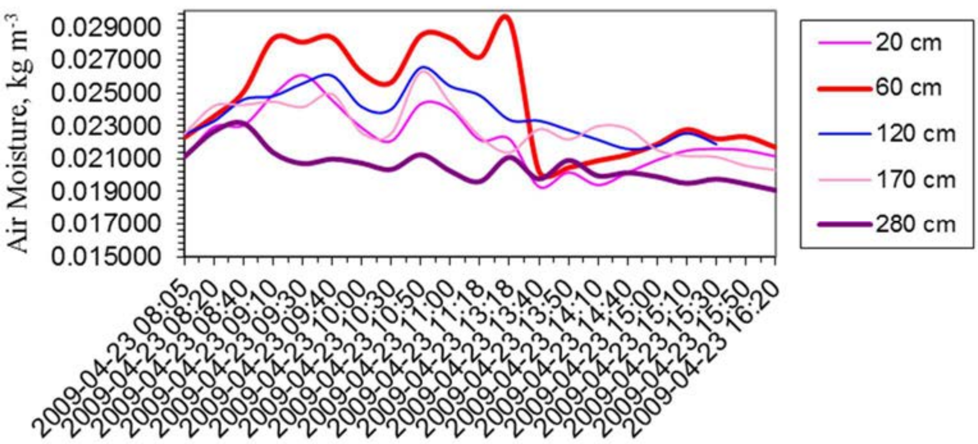

FIG. 6. Variation of the air moisture content along the coffee canopy with time.

3.2. E and T component of coffee trees in different development stages

Fig. 7 depicts the Keeling graph constructed as a relationship between isotopic compositions of oxygen-18 ($\delta^{18}O$, ‰) in the air moisture along the coffee canopy and the inverse of the air moisture content (m^3/mMol). The data were collected during the bean development (April–August) (Fig. 7).

As seen from Fig. 7, the oxygen-18 composition in evapotranspirative moisture ($\delta^{18}O_{ET}$) was –10.91‰ (Eq. 1). The $\delta^{18}O$ of moisture in surface soil ($\delta^{18}O_{E}$) and from the skin of the plants ($\delta^{18}O_{T}$) was found to be –13.85 and –10.34‰, respectively. With these data one can estimate the contribution of individual T and E component of the plant during the bean development stage as much as 84 and 16%, respectively (Eq. 2). This approach was applied to separate T from E of coffee plants in other stages and the results are summarized in Table 2.

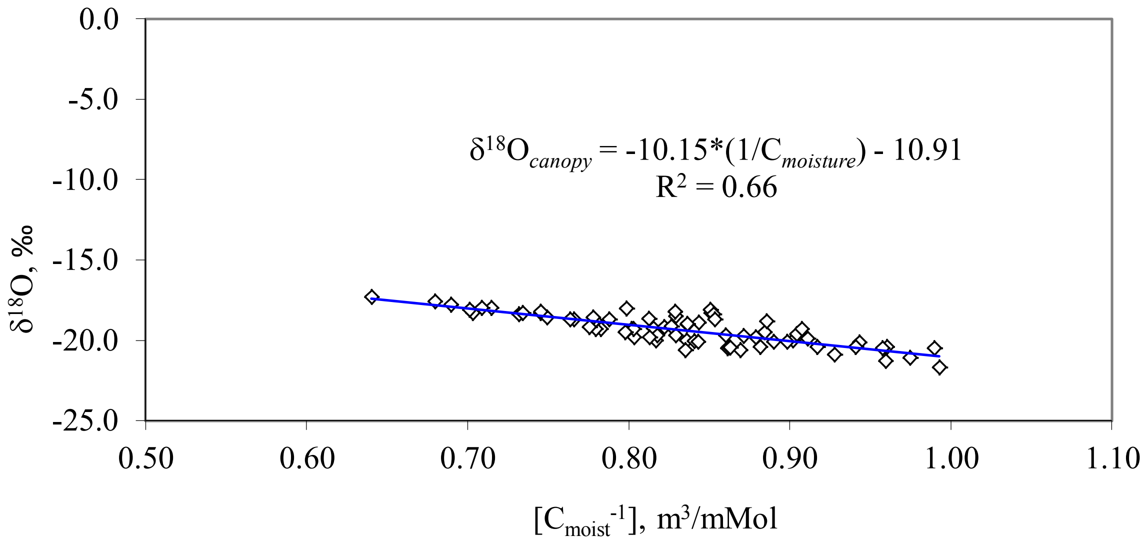

FIG. 7. The Keeling plot derived for coffee trees (Robusta) of ten year old in the bean development stage (April), no irrigation (Da Ha village, Kon Tum province).

FIG. 8. Picture showing coffee plants (Robusta) in the bean development stage.

TABLE 2. T AND E OF 10 YEARS OLD COFFEE PLANTS BEFORE IRRIGATION AS SEPARATED BY ISOTOPIC TECHNIQUE FOR THE THREE IMPORTANT STAGES IN A CROPPING SEASON. FIGURES IN BRACKETS STAND FOR STANDARD DEVIATION IN PERCENT OF THE MEAN VALUES DERIVED FROM THREE EXPERIMENTS IN 2009–2011

Stage in one cropping season of coffee plants (at the Tay Nguyen highland, Viet nam	δ_{ET}, ‰	δ_E, ‰	δ_T, ‰	F_T, %	F_E, %
Maturing and canopy reforming (Sep–Nov)	-11.64 (5)	-12.72 (10)	-10.43 (7)	47 (3)	53 (3)
Budding and flowering (Dec–Feb)	-9.71 (7)	-11.85 (6)	-10.52 (10)	85 (2)	15 (2)
Bean development (Apr–Aug)	-10.91 (3)	-13.85 (5)	-10.34 (5)	84 (2)	16 (2)

Figures 9 and 10 show pictures of coffee plantation in the flowering and maturing stages, respectively.

FIG. 9. Coffee plants in its flowering stage (Feb–Mar).

FIG. 10. Coffee plants in its maturing stage (Oct–Nov).

As seen from Table 2, during the maturing and canopy reforming stage (Sep–Nov) the T was lower (47±3%) than E (53±3%), but during the budding and flowering stage (Feb–Mar) and bean development it was reverse, i.e. T was higher than E (Table 2). Comparing E component of coffee in the three development stages one can see that in the budding and flowering stages following the bean development stage the crop needs more water than other stages. However, the period of bean development (Apr–Aug) it is coincident with the rainy season. During the rainy season, sometimes the soil was saturated with water and coffee could sustain without irrigation. Hence, in order to have high yield of coffee bean, it is vital to irrigate the crop and maintain soil moisture at a level of at least 18–20% (Eq. 4) during the flowering period.

Table 3 shows the T component before irrigation of coffee trees in the flowering stage (Feb–Mar) under mulch and no mulch as separated by the isotopic technique. It is clear that under mulch the transpiration component is higher (94±2%) than under the condition of no mulch (85±2%) meaning that mulch improved the WUE of coffee plants. Mulching with crop residues was proven to be the cheapest way to reduce evaporation as it decreases surface temperature, contributing to the improvement of WUE [14]. Reduction of evaporation and increase of transpiration component by mulch was explained by the fact that the mulching materials generally reflect more solar radiation and have lower thermal conductivity than soil [15]. Mulching with crop residues improves WUE of diverse crops, e.g. tomato [16], maize [17] [18], wheat [19] and rice [20].

TABLE 3. THE T COMPONENT (F_T, %) BEFORE IRRIGATION OF COFFEE TREES DURING ITS FLOWERING STAGE (FEB–MAR) UNDER MULCH AND NO MULCH. FIGURES IN BRACKETS STAND FOR STANDARD DEVIATION IN PERCENT OF THE MEAN VALUE DERIVED FROM THREE EXPERIMENTS IN THE 2009–2011

Parameter	With mulch	No mulch
δ_{ET},‰	-9.42	-9.71
δ_{E},‰	-11.71	-11.85
δ_{T},‰	-9.27	-10.52
F_T, % (Eq. 2)	94 (2)	85 (2)

As seen from Table 4, DI combined with mulching increases T component of coffee plants by around 10% compared to the FI and no mulch practice. However, the T in the DI with no mulch was not much deviated from that of the traditional FI and no mulch (Table 4). This finding could be explained by the fact that the LAI of the crop was high (LAI of 6–7) and the trees were inter-covering on each other making the solar radiation on the soil surface in the both cases to be almost the same. This was supported by the fact that the soil surface temperature in the FI and DI (no mulch) during the time period of the experiment was almost in the same level (data not shown). In the former practice the soil surface temperature was 26.8±0.1°C and in the latter practice it was 27±0.2°C. However, surface soil in the FI was wetter compared to that in the DI. It seems that water in the FI was lost mainly through runoff and/or deep percolation.

TABLE 4. T COMPONENT OF COFFEE PLANTS AS SEPARATED BY THE ISOTOPIC TECHNIQUE IN THE FLOWERING STAGE (FEB–MAR) UNDER DIFFERENT IRRIGATION PRACTICES. UNCERTAINTY OF THE ESTIMATE WAS WITHIN 5–7%

Irrigation practice	T (%)	E (%)
Furrow, no mulch	83	17
Drip, no mulch	87	13
Drip with mulch	94	6

3.3. Water use efficiency of coffee plants (robusta) under furrow (no mulch) and drip irrigation with mulch

Table 5 shows the data used to estimate the WUE of coffee (Robusta) under different irrigation practices. The data included the bean yield, amount of irrigated water and the WUE was estimated based on Eq. 5.

TABLE 5. COFFEE BEAN YEILD, AMOUNT OF IRRIGATED WATER IN DIFFERENT IRRIGATION PRACTICES AND WUE OF COFFEE (Robusta) PLANTED AT THE TAY NGUYEN PLATEAU, CENTRAL VIET NAM

Irrigation practices	Y, kg/ha	Irrig. water, m^3/ha	WUE, kg/m^3
Furrow irrigation, no mulch	3 200	2 882	1.11
Drip irrigation, no mulch	3 500	1 995	1.75
Drip irrigation, with mulch	3 800	1 784	2.13

As seen from Table 5 the WUE of coffee plants under DI with mulch is the highest (2.13 kg/m^3) and it is the lowest under FI and no mulch (1.11 kg/m^3). WUE of coffee crop under DI improved by 31 and 36%, respectively, without mulch and with mulch compared to that under FI and no mulch (Table 5). Low yield of coffee bean under furrow irrigation leading to the lowest WUE of the crop might be due to the fact that furrow irrigation made soil within the rooting zone to be too wet preventing the secondary roots to develop. This reduces water to uptake nutrient by the plants. Moreover, under the wet condition root rot disease could occur as it was observed for chilian pepper with Phytophthora [21] leading to lower crop yield.

Supposed that DI combined with plant residues mulching to be applied to the total 290 000 ha of coffee at the Tay Nguyen plateau then 3.2 billion cubic meter of water could be saved and the local farmers could gain an extra profit amounted in 295 800 ton of coffee bean or around US $ 590 000 at the London coffee market.

4. CONCLUSIONS

Due to the photosynthesis activity in the morning and noon time coffee plants (Robusta) actively transpire making the air under the canopy to be moister compared to the air above the canopy. However, afternoon the photosynthesis seems to slow down leading to moisture in the air under and above the canopy to be close to each other. Supplement irrigation would better be carried out in the morning.

Over a coffee cropping season the crop needs more water during the flowering stage so supplement irrigation is required to maintain the soil moisture at a level of 18–20% (Field capacity of the soil). Compared to the traditional furrow irrigation practice, drip irrigation combined with plant residues mulching reduced the evaporation by almost 10% leading to the improvement of the irrigation WUE up to 90%. This allows the local farmers to gain an extra profit amounted to around two thousand (2 000) US Dollor per ha of their coffee crop. Drip irrigation combined with plants residues mulch is advised to the local farmers to apply for all coffee plantation at the Tay Nguyen area.

ACKNOWLEDGEMENTS

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USING ISOTOPES AND MICROMETEOROLOGY TO QUANTIFY SOIL EVAPORATION AND PLANT TRANSPIRATION

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Abstract

Independent analyses of the partitioning of evapotranspiration from a wheat crop into soil evaporation (E) and plant transpiration (T) were made through isotopic analysis of $\delta^{18}O$ and $\delta^{2}H$ in the soil water and the water vapour in and above the canopy and by a micrometeorological technique and by Inverse Lagrangian (IL) dispersion, that infers the source strengths of water vapour in the canopy from its concentration profile and canopy turbulence There was very good agreement between the two approaches, the isotope analysis giving E as 4% of ET and the IL technique as 6%.

1. INTRODUCTION

Isotope fractionation has been used in recent years to separate the components of evapotranspiration (ET) into soil evaporation (E) and plant transpiration (T) [1]. As described in other papers in this TECDOC, the technique estimates the ratio of T to ET. However, without further information on the magnitude of ET, it cannot estimate the magnitudes of the components. To accomplish this, the study used the micrometeorological technique of eddy covariance to determine ET for a developing crop of winter wheat in conjunction with measurement of enrichment of the isotopes $\delta^{18}O$ and $\delta^{2}H$ in the vertical profiles of water vapour within and above the crop canopy. The study also employed a second micrometeorological technique, based on a Lagrangian description of turbulent transport [2] in the canopy to infer E at the soil surface and T from the various foliage layers in the canopy [3].

2. METHODS

2.1. Crop

The study was conducted in a large field of winter wheat at the BOKU University experiment station near Vienna in late April 2012. At the time of the study, the wheat was 0.23 m high and had a leaf area index of approximately 1.

2.2. Isotope measurement

The concentration and isotopic composition of water vapour within and above the wheat canopy were measured continuously for several days with a cavity ringdown spectroscopy (CRDS) (Picarro L1115-i water isotope analyzer) (Fig. 1A). Here the results for three consecutive days were reported when water vapour measurements were made at heights of 0.02, 0.09, 0.16, 0.23, 0.75 and 1.5 m above the soil surface and the surface soil had dried to a mean volumetric water content of 10.6%. Its mean temperature was 15.6°C.

FIG. 1. (A) Picarro L1115-i water isotope analyzer connected to its 6 air intakes; (B) 3-D sonic anemometer and LI-COR 7500 water vapour sensor mounted at 2.5 m at top of mast.

2.3. Isotopic analysis

The fractional contribution of transpiration to evapotranspiration (F_T), is given by:

$$F_T\,(\%) = \frac{\delta ET - \delta E}{\delta T - \delta E} \times 100 \qquad (1)$$

where δE is the $\delta^{18}O$ of the water vapour evaporated from the soil surface, δET is the $\delta^{18}O$ of the water vapour evaporated from the crop canopy, and δT is the $\delta^{18}O$ of the transpired water vapour [4].

2.4. Evapotranspiration measurement

The micrometeorological technique of eddy covariance was employed to measure ET at 2.5 m above the ground. ET is calculated as:

$$ET = \overline{w'c'} \qquad (2)$$

where w denotes the vertical wind speed at the height of measurement, c the atmospheric concentration of water vapour measured simultaneously at the same point as w, the primes indicate deviations from the mean values over the measuring period and the overbar the mean of w'c' over the sampling period. w was measured with a Campbell CSAT3 sonic anemometer and c with a LI-COR 7500 CO_2/water vapour sensor; see Fig. 1B. Measurements were made rapidly at a sampling frequency of 10 Hz in order to sample the main eddies involved in gas transport and processed data were organised into 30-min means.

2.5. Measurements of E and T within the wheat canopy

The within-canopy data were analysed by an inverse Lagrangian (IL) dispersion analysis which infers source and sink strengths of water vapour at the soil surface and in the various canopy layers. The analysis provides a means of linking canopy sources and sinks with mean concentration profiles using statistics of the turbulence in and above the canopy. The input data can be calculated from the measurements made by the 3-D sonic anemometer.

3. RESULTS

3.1. Water vapour concentrations and meteorological data

Profiles of vapour pressure measured by the Picarro laser spectrometer on one of the example days, 26 April, are shown in Fig. 2. Vapour pressure gradients were small over night, e.g. at 08:00 and 22:00, but surprisingly large gradients developed by day, even inside the small 23 cm canopy. The meteorological data were filtered for low wind speeds and periods of extreme thermal stability in the atmosphere. Filtering removed 44% of a potential 421 30-min runs.

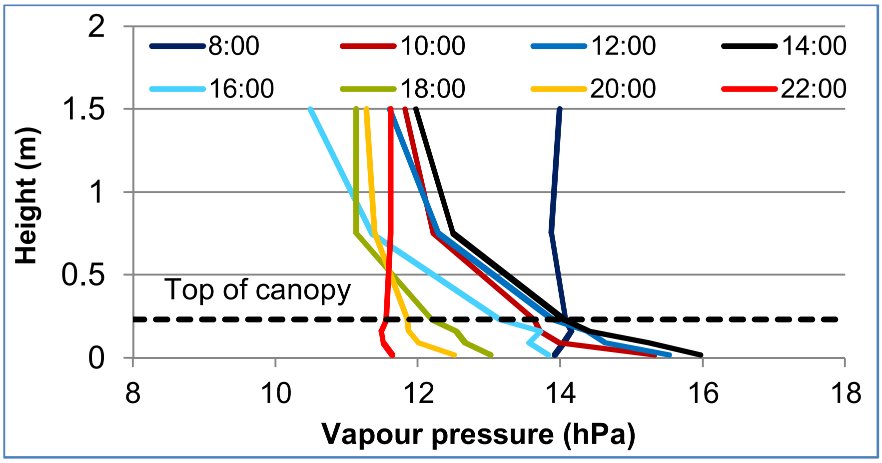

FIG. 2. Profiles of water vapour concentration (expressed as vapour pressure) within and above the wheat canopy on 26 April.

3.2. Soil evaporation and plant transpiration rates estimated by il and isotopic techniques

Due to the dryness of the soil surface, estimated E was quite small, but nevertheless, the analysis showed it to be declining slightly, from 0.012 mm/h to 0.009 mm/h as the soil dried from 13% to 9% while T increased from 0.18 mm/h to 0.23 mm/h. It is encouraging that both the $\delta^{18}O$ isotopic and IL techniques were in good agreement although they rely on quite different approaches (Fig. 3).

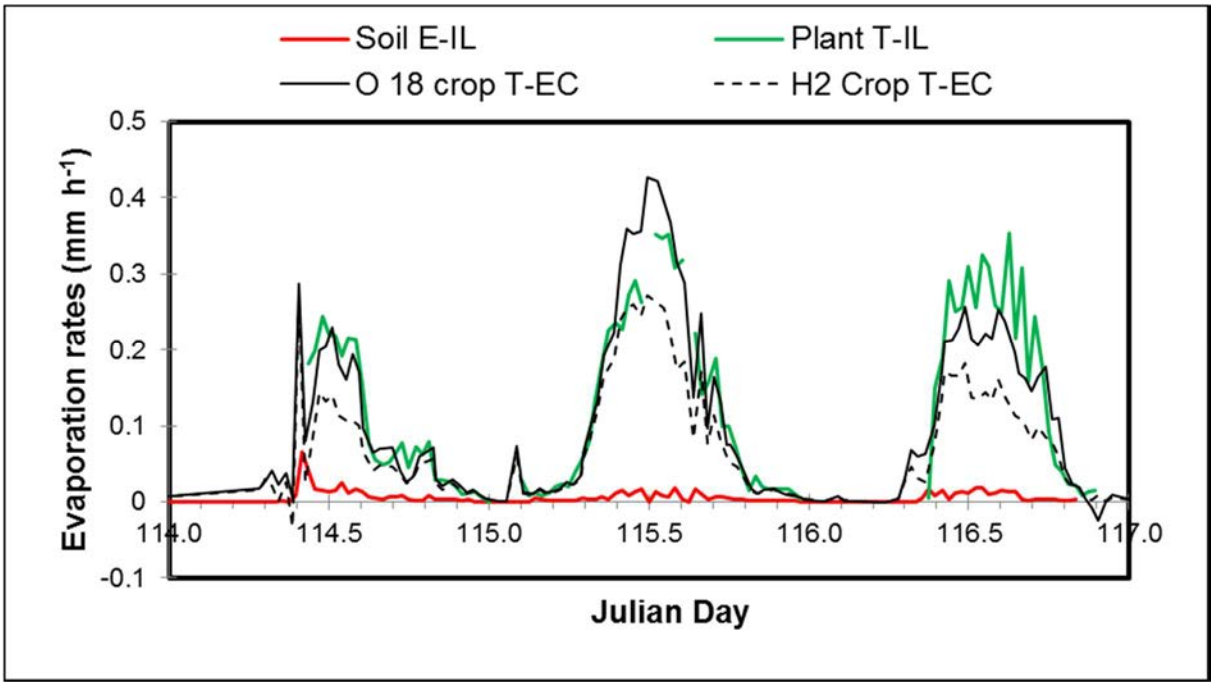

FIG. 3. E and T estimated by the IL technique, (Soil E-IL) and (Plant T-IL), respectively, and T from isotopic analysis using $\delta^{18}O$ and $\delta^{2}H$ to partition the ET measured by eddy covariance into E and T (O18 crop T-EC and H2 crop T-EC), respectively.

The IL and the isotopic analyses gave essentially the same partitioning of ET into E and T. For 3 example days on a dry soil, isotopic analysis using δ^{18}O gave E/ET~4% and T/ET~96%, while IL analysis gave corresponding figures of 6% and 94% (Fig. 4).

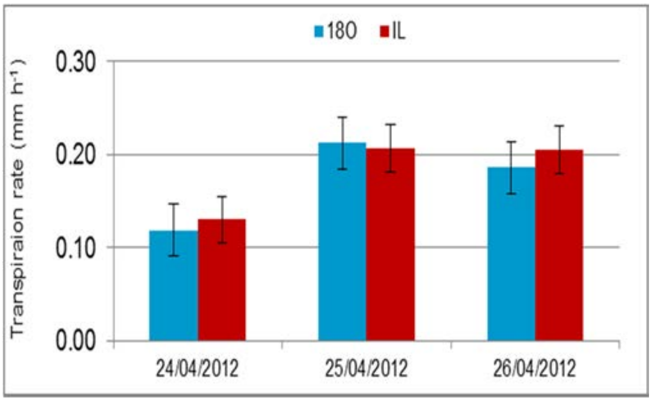

FIG. 4. Average daytime transpiration rates determined by $\delta^{18}O$ and IL analyses.

The use of the IL analysis to determine water vapour in different segments of the canopy is illustrated in Fig. 5. In these observations the soil was dry (9–12 %) and soil evaporation was small.

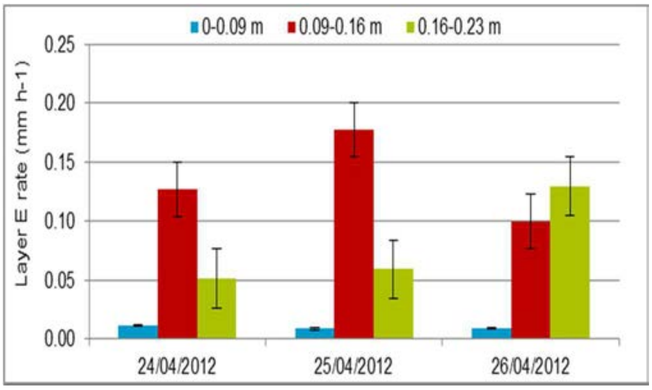

FIG. 5. Daytime means and standard errors of evaporation rates from canopy layers using IL analysis.

4. CONCLUSIONS

The study showed that the eddy covariance approach (virtually an assumption-free direct method) confirmed the correctness of the IL analysis for the total water loss from the canopy (to within 6%). The study was a nice confirmation of different approaches, but while validating the predictions of the isotopic analysis in this instance, it should be repeated with a higher LAI and a higher soil moisture content.

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ISOTOPE MASS BALANCE METHOD TO PARTITION EVAPORATION AND TRANSPIRATION IN CROPPING FIELD

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Abstract

Stable isotope compositions (δ^2H and $\delta^{18}O$) of soil water can reveal information about soil water fluxes (e.g., evaporation (E), transpiration (T), and downward percolation) that are generally difficult to obtain by other techniques. Evapotranspiration, the sum of E and T, is a continuous process occurring in the soil-crop-atmosphere system. Because E causes fractionation of isotopes in soil water while T and downward percolation does not, equations that conserve mass and isotopes can be used to quantify evaporative vs. non-fractionating losses. By knowing the isotopic composition of water pools of soil, irrigation, and rainfall in a given period, fluxes of E and T can be separated using the mass balance both of the amount and isotopes of the water in the soil-cropping system. Here, a detailed protocol of Isotope Mass Balance (IMB) to partition E and T in cropping system is provided, including its principle, main equations, general assumptions, parameterization, operation procedure, and sensitivity analysis. An example of using IMB to separate E and T in winter wheat and spring maize systems in the North China Plain is also given with the emphasis on the operation details. To make IMB more practical, a worksheet in Microsoft Excel of IMB method is also provided.

1. INTRODUCTION

In agriculture, irrigation water and/or rainfall water are always expected to be used as much as possible for crop biomass production. Any kind of water loss from soil not directly related to crop growth, like evaporation (E), drainage, and runoff, should be reduced as the first priority. E, the loss of water from soil to air via a change of phase, is a natural process and is not easily differentiated from plant transpiration under field conditions. Transpiration (T) is another process of water loss in gaseous form. However, to assess the effects of agronomic practices like straw mulching and plastic filming on evaporation reducing, E must first be differentiated from T.

E and T are different in their water molecular isotope signatures. During the change from liquid to vapour in E occurring at the surface soil, there is another change occurring within the liquid water: fractionation of isotopes: ^{18}O and ^2H. Due to the tiny difference in diffusion speed and evaporation energy among molecules of $^1H_2{}^{16}O$, $^2H^1H^{16}O$, $^2H_2{}^{16}O$, $^1H_2{}^{18}O$, $^2H^1H^{18}O$, and $^2H_2{}^{18}O$, the degree of enrichment of ^{18}O and ^2H in residual liquid water and emitted vapour in E are different, the so-called isotope fractionation. Consequently, soil evaporation alters both the soil water content and the soil water isotopic composition. In contrast, T, which is the loss of water through stomata and cuticle, does not fractionate soil water isotopes at steady state, occurring on most occasions. Thus, under general condition, the isotopic composition of the outgoing flux, or transpired vapour, is the same as that of the incoming flux, or stem water, which is derived from soil water [1], [2], [3]. This difference in isotope fractionation between E and T is the basis of the isotope method to partition E and T.

Generally, two kinds of isotope methods to separate E and T have been developed, isotope mass balance (IMB) [4]5] and Keeling Plot [5], [7]. Compared to Keeling Plot, IMB is a simple technique for the estimation of the time-averaged fluxes of E and T in field condition. The pioneering work on this was carried out in grass systems in Hawaii with different rainfalls [4]. With improvement in determining the average soil water isotope composition, IMB was used to separate E and T in two sites along a climate gradient on the east side of the Cascade Mountains, in Washington, USA, including water input in forms of melting snow [8]. With isotope composition of water pools (leaf, root, standing water and soil water), IMB was also used to assess E and T of a freshwater marsh system [9]. In controlled condition, IBM has been applied to laboratory lysimeter [10] or climatic chamber [11] to study the transpiration processes of plant.

IMB is a simple method to partition E and T, because of its reliance on mass balance of both the amount (mass) and isotopes of water. Meanwhile, it is also simple in operation and can be used for plot experiments in the field, because it does not measure the isotope composition of water vapour, which is generally a difficult task in the field. However, its result is only a time-averaged estimation of soil evaporation for a given period within the entire crop.

2. PRINCIPLE

Evaporation causes enrichment of $\delta^{18}O$ and $\delta^{2}H$ in the near surface soil water and depletion in the emitted vapour, while T does not cause significant fractionation of $\delta^{18}O$ and $\delta^{2}H$. This makes the isotopic signatures of E and T different. During the measurement of E and T, water is mass-balanced between the beginning and end of the study period. Thus, by the mass balance of both the amounts (mass) and isotope composition of water, E and T can be separated directly.

2.1. Assumptions

Although the principle of IMB is physically clear and simple, it needs a series of assumptions to make the principle workable, the steps detailed, and the result reliable:

(1) As time-series soil samples are to be taken from different positions, the spatial variation of soil water content and isotope composition of the soil water within the sampling area is assumed minimal and can be ignored.
(2) The lateral movement of the soil water is assumed minimal. It is also assumed that there is no isotope fractionation when liquid water is moving within the soil profile (upward and downward).
(3) The isotope composition of irrigation water and rainfall samples have the same value as the water entering into the soil, meaning there is no isotope fractionation when these waters stayed at the soil surface.
(4) Any atmospheric vapour condensation on the soil surface or on the plant that enters into the soil profile (e.g. dew), or evaporated vapour re-condensed in soil pores, is considered small enough to be neglected.
(5) There is no or negligible preferential flow through soil macro-pores.
(6) The irrigation and/or rainfall are supposed to occur as a single event immediately after the period beginning at t_1, and E and T occur continuously until the period end at t_2.
(7) Although E can occur theoretically anywhere in the soil profile, especially the upper 20 or 30 cm, a supposed depth, here set at 5 cm beneath the soil surface, is used as the site of evaporation. The average temperature at 5 cm beneath the soil surface is used to determine the isotope fractionation factor, α.

(8) At 5 cm beneath the soil surface, water vapour is in isotopic equilibrium with liquid water in the 0–10 cm soil layer. The activity of water in soil is also the same as the pure water. Meanwhile, there is no kinetic isotopic fractionation in the evaporation occurring within the soil profile.

(9) The isotope composition of transpired water is the composition of the mixture of initial soil water, rainfall, irrigation and final soil water.

2.2. Main equations

For a given soil with a certain depth, the aimed soil depth (which needs to be defined according to one's purpose), the amount and isotopic (^{18}O and ^{2}H) composition of water are balanced within a given period (Fig. 1), which can be expressed as:

The mass balance of water:

$$W_{t2} - W_{t1} = Q_i + Q_r + Q_u - Q_e - Q_t - Q_s \quad (1)$$

The isotope composition balance of water:

$$(W\delta)_{t2} - (W\delta)_{t1} = Q_i\delta_i + Q_r\delta_r + Q_u\delta_u - Q_e\delta_e - Q_t\delta_t - Q_s\delta_s \quad (2)$$

where:

W: the amount of soil water within a given depth, kg/m^2;
Q: the amount of water put into or run out of soil, kg/m^2;
δ: isotope composition ($\delta^{18}O$ or $\delta^{2}H$) of water, ‰;
Subscript t1 and t2: beginning time and end time of the given period, respectively;
Subscript i, r, u, e, t, and s: irrigation water, rainfall, upward of soil water, evaporation, transpiration and seepage, respectively.

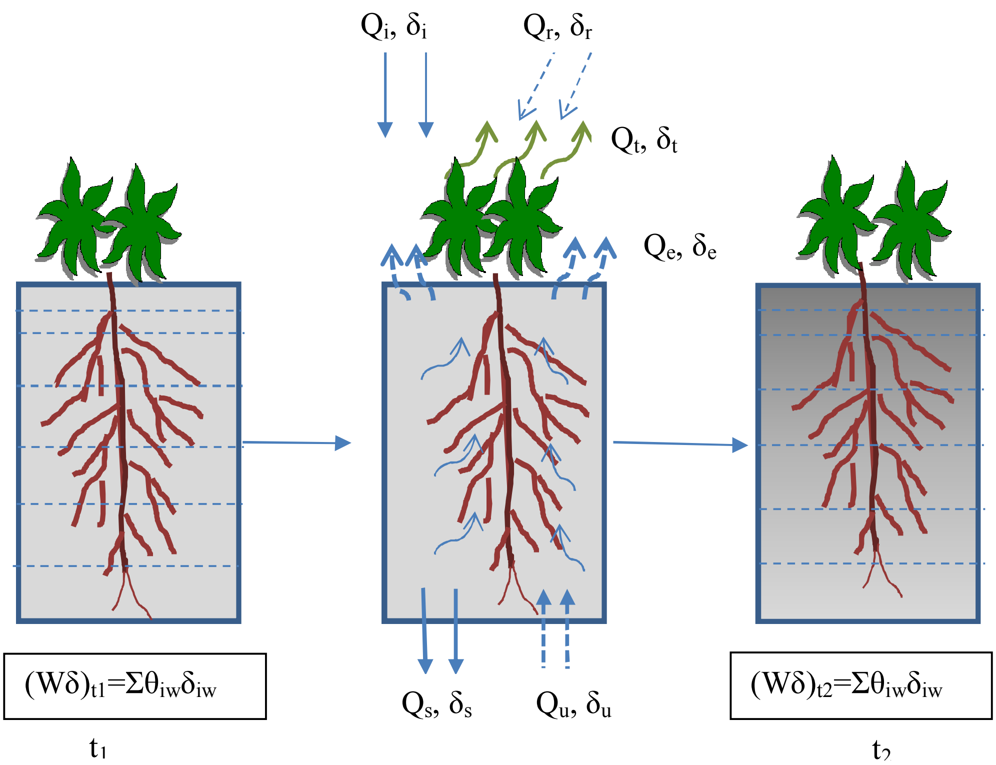

FIG. 1. Schedule explanation of the principle of Isotope Mass Balance (IMB) method for partitioning evaporation and transpiration in cropping field. See the text for the meanings of the symbols.

3. PARAMETERIZATION

(1) W. Amount of soil water within a given soil depth must be measured in sections (20 cm or 10 cm each), as the soil water content is generally not evenly distributed along the soil profile. The top 20 cm or 30 cm soil layer is critical in IMB, and a 5 cm-length segment is strongly recommended in water content measurements. As soil water must be extracted for isotope measurement, oven drying method is recommended to measure the soil water content of each section.

(2) Q_i. The amount of water of each irrigation event should be recorded accurately by a water meter. In sprinkler irrigation, to obtain a more accurate irrigation amount, the interception coefficient of the crop to irrigation water should be considered.

(3) Q_r. The amount of each rainfall event should be recorded accurately by raingauge. Use of the interception coefficient of the crop to rainfall is recommended to obtain the real amount of rainfall entering into the soil.

(4) Q_μ. The amount of upward water e.g. capillary rise, entering into the aimed soil body should be quantified.

(5) Q_s. The amount of seepage water leaving the aimed soil body should be quantified.

(6) δ_i. The $\delta^{18}O$ and δ^2H of the irrigation water should be measured accurately. Representative water samples of each irrigation event should be taken and measured.

(7) δ_r. The $\delta^{18}O$ and δ^2H of rainfall water should be measured accurately. Representative samples of rain water should be taken at each rainfall event.

(8) δ_u. The $\delta^{18}O$ and δ^2H of the water in the 20 cm soil beneath the boundary of the aimed soil body should be measured accurately.

(9) $\delta_{s.}$ The $\delta^{18}O$ and δ^2H of water in the 20 cm soil above the boundary of the aimed soil body should be measured accurately.

(10) δ_e. In the IMB method, the δ_e is not measured directly, but calculated based on the quantitative relationship of isotope fractionation between liquid and vapour, which has been experimentally obtained from many studies, using the equations of Majoube [12]:

$$\ln\alpha_{v\text{-}l} = 1137 / T^2 - 0.4156 / T - 0.0020667, \quad \text{for } ^{18}O \tag{3}$$

$$\ln\alpha_{v\text{-}l} = 24844 / T^2 - 76.248 / T + 0.052612, \quad \text{for } ^{2}H \tag{4}$$

are used to obtain $\alpha_{v\text{-}l}$, where T is the absolute temperature (K).
Then δ_e is calculated using $\alpha_{l\text{-}e} = (\delta_l + 1000) / (\delta_e + 1000)$

$$\delta_e = \frac{\delta_l + 1000}{\alpha_{v-l}} \tag{5}$$

Here, the assumption is made that the evaporation of soil water only occurred at a few cm (e.g. 5 cm) beneath the soil surface at an average T during the given period.

(11) δ_t. Isotope composition of the transpired water is assumed to be the average of the soil water absorbed by roots. In practice, it is calculated as the weighted-mixture of soil water in the root zone at t1 and t2, the water of irrigation, and the rainfall water.

$$\delta_t = \frac{(W\delta)_{t1} + (W\delta)_{t2} + Q_i\delta_i + Q_r\delta_r}{W_{t1} + W_{t2} + Q_i + Q_r} \tag{6}$$

Here, the root depth of the zone is dynamic according to the growing stage and the variety of the crop. In this study, the rooting depth was set at 10–60 cm as the standard root zone in IMB.

(12) δ_s. It is reasonable to assume that the isotope composition of soil water leaving the boundary of the aimed soil body is the average of the soil water in the 20 cm soil layer above the boundary between t1 and t2.

$$\delta_s = \frac{(W_{20}\delta_{20})_{t1} + (W_{20}\delta_{20})_{t2}}{(W_{20})_{t1} + (W_{20})_{t2}} \tag{7}$$

where W_{20} and δ_{20} are the water content (kg/m^2) and isotope composition (δ, ‰) in the 20 cm soil layer above the boundary, respectively.

4. OPERATIONAL PROCEDURE

(1) Irrigation and rainfall recording. The amount of water for each irrigation and rainfall event must be recorded properly.

(2) Irrigation and rainfall water sampling. Representative water samples of each irrigation and rainfall must be obtained for isotope measurement.

(3) Soil temperature recording. Temperatures at 5 cm beneath the soil surface should be recorded automatically. This temperature is critical to calculate δ_e. Temperatures down the soil profile are recommended to be measured for more accurate E estimation.

(4) Soil water content measuring. Fresh soils of 0–5, 5–10, 10–20, 20–40, and 40–60 cm (the depth depending on the root distribution or the purpose) are taken out by drill and put into air-tight plastic bags immediately. To be representative, three to 5 replicated soil samples are needed. The water content of each soil sample is measured with oven-drying method.

(5) Soil water sampling for isotopic determination. For soils from 0–5 and 5–10 cm (sometimes 10–20 cm), which generally have low water contents, vacuum distillation (under a vacuum of 110 Pa) is recommended to extract the water from the soil. For soils from the deeper layers, which generally have high water contents, high-speed centrifugation is recommended. To do so, centrifugal cutting rings are filled with soil samples of the same weight to make sure of the mass balance achieved. For our system, the rings are centrifuged at 11 000 rpm (about 15.5 bar) for 1h at 4°C. Water samples are frozen preserved in plastic bottles until isotope measurement.

(6) Isotope of water samples measurement. $\delta^{18}O$ and $\delta^{2}H$ of water samples of soil, irrigation, and rainfall should be measured properly with a mass spectrometer or other isotope equipment. The quality of the measurement should be kept as good as possible.

(7) E and T calculation. Based on the main equations of the IMB method, a worksheet in Microsoft Excel is developed to calculate E and T. With the completed data input, results can be easily obtained.

5. SENSITIVITY ANALYSIS

The result of IMB is the time-averaged flux of E and T during a given period, and many parameters are needed to calculate it. The effects and sensitivity of each parameter (e.g. the quantity of rainfall or irrigation (Q_r), the average isotope composition of rainfall (δr), average temperature at 5 cm beneath the soil surface (T_5), average of soil water in 0–10 cm layer (δ_{51}), average $\delta^{18}O$ of water in 10–60 cm soil (δ_t), and their combinations on the calculated E and T) are shown in Table 1. For the details of the field experiment used, one can find them in [13].

As shown in Table 1, if the water quantity of rainfall or irrigation was measured with an error of 10%, the maximal error of E and T is only –2.7% and +2.5%, respectively, meaning Q_r or Q_i is not sensitive factor in IMB method. Accordingly, we can find that δ_t, the average $\delta^{18}O$ value of water in 10–60 cm of soil, the roots zone, during the period, is the least sensitive factor in IMB. On the other hand, the average $\delta^{18}O$ value of water in 0–10 cm of soil, the evaporation front, is the most sensitive factor in IMB, a 10% error will make +18.9% to -3.5% error –8.6% to +6.2% for T, respectively. This means the choice of the depth of the evaporation occurred in soil profile and the measurement of isotope composition of water in this relative dry soil are very important for IMB calculation.

Meanwhile, for a given length of the period, the more recharges, the more errors of the result, because each recharge event resets the value of water that is utilized by the crop. It is reported that variations of 5‰ in δ_t values can result in no variations in the fraction of E, but up to 0.2 in T [4].

TABLE 1. EFFECTS OF EVAPORATION DEPTH, ROOT DEPTH, AND SOIL TEMPERATURE AT –5 CM ON THE EVAPORATION RATIO (%) CALCULATED BY IMB

	E (mm)	T (mm)	Change in E (%)	Change in T (%)
Standard	37	81	-	-
Qr, +10%	37	83	0	2.5
–10%	36	80	–2.7	–1.3
δr, +20%	34	84	–8.1	3.7
–20%	40	78	8.1	–4.9
T_5, +20%	40	78	8.1	–4.9
–20%	39	79	5.4	–2.5
δ_{5l}, +20%	44	74	18.9	–8.6
–20%	32	86	–13.5	6.2
δt, +20%	37	81	0	0
–20%	37	82	0	1.2
Qr, +10%; δr, +10%	34	83	–8.1	2.5
Qr, –10%; δr, –10%	40	80	8.1	–1.3
T_5, +20%; δ_{5l}, +10%	41	71	10.8	–12.3
T_5, –20%; δ_{5l}, –10%	33	85	–10.8	4.9

†Standard: (Qr): rainfall 15.2 mm; (δr): average $\delta^{18}O$ of rainfall (‰), 11.842; (T_5): average T at –5 cm in soil (C) 8.1; δ_{5l}: average of soil water in 0–10 cm layer (‰), 7.501; (δ_t): average $\delta^{18}O$ of water in 10–60 cm soil (‰), –8.922.

Differences in the isotopic composition of water pools of soil, irrigation, and rainfall, and fluxes of evaporation and transpiration can be used to construct the equations of isotopic mass balance in the soil-cropping system. These equations have the ability to quantify the time-averaged flux of both evaporation and transpiration. The isotope mass balance method has a physically clear principle and is simple in operation. It does not need to measure isotope composition of vapour and is especially suitable for small plot experiments.

The successful use of isotope mass balance to partition evaporation and transpiration depends heavily on the achievement of all assumptions, reasonable parameterization, and careful procedure. With the worksheet provided in Microsoft Excel, evaporation and transpiration flux can be calculated directly.

In the isotope mass balance method, the choice of the depth of evaporation occurring under the soil surface, the measurement of the isotope composition of the water in the top soil layer, and the sampling frequency of the water of the top layer are the most important factors for obtain good result. Meanwhile, the period should not set to be too long, due to the big error in the estimation of the isotope composition of the soil water lost by transpiration.

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SEPARATION OF EVAPORATION AND TRANSPIRATION IN WINTER WHEAT AND SUMMER MAIZE CROPPING SYSTEM IN NORTH CHINA PLAIN WITH WATER ISOTOPE MASS BALANCE METHOD

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Abstract

Evapotranspiration, including evaporation and transpiration, is a continuous process occurring in soil-plant-atmosphere continuum. It is one of the major components in the farmland water cycle. In a two-year field experiment, isotope mass balance (IMB) method was used to separate evaporation (E) and transpiration (T) under different agronomic practices in the winter wheat and summer maize cropping system in North China Plain. Soil water content, isotopic (δ^2H and $\delta^{18}O$) values of soil water, rainfall, and irrigation water were measured periodically. Results showed that IMB can be used to separate E from ET in crop field under different agronomic practices.

1. INTRODUCTION

Water scarcity is a major factor limiting agricultural production all over the world. With the onset of global climate change, the impact of drought stress on crop yield is becomes more severe, especially in regions suffering from irrigation water shortage. Thus, for sustainable agricultural development, improved agricultural water management practices must be established to use the available water resources more efficiently.

The production of sufficient food for the huge population (1.3 billion) has always been a priority for China. About 70% of the fresh water is used in agriculture in China, but water use efficiency is relatively low. In the North China Plain, for example, by improving the current irrigation practices, 30% of irrigation water could be saved without reducing the yields of wheat and maize [1]. For agricultural sustainability in Northern China, it is vital to develop management practices for improving water productivity.

In the North China Plain, the majority of the irrigation water came from the Yellow River and the Hai River, and with about 600 mm annual precipitation, winter wheat and summer maize production suffers badly from irrigation water shortage under the monsoon climate. In the winter wheat growing season, the precipitation is only ca. 150 mm. Consequently about 3 000 m^3 ha^{-1} groundwater is required for producing a 3 500–4 000 kg/ha wheat and 1.08 for summer maize [2]. Field measurements and modeling results showed that 30 to 50 % of the irrigation water was lost through deep drainage because of inappropriate irrigation practices [1], [3]. This amount of irrigation water could be saved without reducing winter wheat yield. Generally, soil evaporation is considered to be water loss without significant benefit to the crop, and crop transpiration is the water consumption for crop growth. Separation between soil evaporation and crop transpiration in the field is important for evaluating water saving agronomic practices and the water use efficiency of the crop. The aim of the project is to use the isotopic method to separate soil evaporation and crop transpiration in a winter wheat and summer maize cropping system in the North China Plain, where irrigation water is under serious shortage.

2. MATERIAL AND METHOD

2.1. Experiment Set Up

The experiment was set up at Shangzhuang Experimental Station of CAU (N 40º08'21.73'', E 116º10'52.58") in Beijing. It has a continental monsoon climate with the highest air temperature of 31°C and precipitation of 179 mm in July and lowest temperature and precipitation in January (2°C and 3 mm precipitation). The mean annual air temperature and precipitation were 11.6°C and 400 mm, respectively in recent years. The typical cropping system was winter wheat-summer maize, from October to June for wheat and June to September for maize. Some properties of the soil of the experiment field are shown in Table 1.

TABLE 1. SOIL PROPERTIES AT FIELD SITE OF CAU

layer (cm)	pH	Bulk density ($g\ cm^{-3}$)	Soil texture (%)* Sand	Silt	Clay	SOM (%)	Porosity %
0–30	7.9	1.63	28	52	20	1.58	39
30–60	7.8	1.73	32	52	16	0.54	35
60–85	7.9	1.56	32	44	24	0.53	41
85–125	8.4	1.70	32	64	4	1.24	36
>125	8.4	1.47	8	72	20	0.50	45

*USDA unit; SOM: soil organic matter

2.1.1. Winter Wheat

The aim of this study was to partition evapotranspiration into soil evaporation and wheat transpiration in field condition. Four micro-plots were set up within a large winter wheat field. The plots were 3 m × 3 m and located randomly in the field. The four treatments were as follows:

(1) Control: The same as the conventional way to produce winter wheat. The water loss was the sum of soil evaporation and crop transpiration.
(2) Only transpiration: The soil surface between plant rows was covered by plastic film to prevent soil evaporation from occurring. Water loss only from crop transpiration.
(3) Bare soil surface after spring: All plants were cut and removed from the plot and water loss was only from soil evaporation.
(4) Bare soil surface after sowing: All small plants were cut and removed from the plot just after germination. The water loss was only from soil evaporation.

The difference between treatments (3) and (4) was the effect of small plants before winter. Measurements taken in the winter wheat experiment were as shown in Table 2.

TABLE 2. MEASUREMENT ITEMS AND METHODS IN WINTER WHEAT EXPERIMENT

Item	sampling method	Sampling date	Samples
Isotopes of irrigation water	Sampling bottle, fully filled with irrigation water	Every irrigation event	Stored at 4°C before measurement
Rainfall water	Collected from rain gauge before transferring to sampling bottles and sealed	Every rainfall event	Stored at 4°C before measurement
Soil water content and isotopes of soil water	5 soil cores at 0–5, 5–10, 10–20, 20–40, 40–60 cm in each plot and combined into 1 sample. Stored in sealed plastic bags.	green-return（4/2） jointing（4/20） flowering（5/10） mature（6/3） period before and after irrigation	Oven drying to determine soil water content Centrifuge to extract water and stored at 4°C in sealed bottles.
Water isotopes of stem water	20 plants were randomly selected within each plot, put into sealed paper bags	green-return（4/2） jointing（4/20） flowering（5/10） mature（6/3） period; samples taken at 2 pm	1) Centrifuge and stored at 4°C in sealed bottles 2) Weigh plant samples after oven drying
Soil temperature	5 cm in each plot	Samples taken at 2 pm every 3rd day	

2.1.2. Summer maize

The aim of this study was to partition the total ET into soil evaporation and maize transpiration under field conditions. Four micro-plots were set up within a large summer maize field. The plots were 6 m×6 m randomly located. The four plots were as follows:

(1) Control: The conventional way to produce summer maize in Beijing. The water loss was the sum of soil evaporation and crop transpiration.

(2) Only transpiration: The soil surface between two maize rows was covered by plastic film to prevent soil evaporation. The water loss was just from crop transpiration.

(3) Bare soil surface: No plants were grown in the plot and water loss was only from soil evaporation.

(4) Partial evaporation: The maize row space was covered by straw to partly prevent soil evaporation occurring. The water loss was from the crop transpiration and the partial soil evaporation.

Soil samples of different layers (0–5 cm, 5–10 cm, 10–20 cm, 20–40 cm, 40–60 cm and 60–100 cm) were collected by soil coring at different times. Maize biomass and stems were collected periodically. Water samples of soil and plant stems for isotopic analysis were obtained from centrifugation of soil cores and stem cuttings.

2.2. Measurement

Extraction of soil water: Centrifugal cutting rings were filled with same weight of soil samples to make sure the mass balance achieved during centrifugation. The four rings were put into a HITACHI Centrifuge (CR22GⅡ, Japan) and centrifuged at 11 000 rpm (about 15.5 bar) for 1 h under 4°C. Water extracted from soil samples was frozen and preserved in plastic bottles.

Isotopic analysis of water samples: The ^2H and ^{18}O of water samples were analyzed with a Picarro isotope laser in 2010 and 2012. The results are expressed using delta (δ) notation in per mil (‰) difference from the Vienna Standard Mean Ocean Water (VSMOW). The measurement accuracy is ±3‰ for δ^2H and ±0.3‰ for $\delta^{18}O$ for MAT-253 and ±1‰ for δ^2H and ±0.2‰ for $\delta^{18}O$ for the Picarro isotope laser, respectively.

2.3. Methods to separate E And T

Comparison: Water loss from common fields (with plants), bare soil and covered soil (with plants) was treated as E and T, E only, and partly E and whole T, respectively. Thus, the difference in soil water content between the common field and bare soil was T, between the common field and covered soil was the effect of covering in reducing E.

Isotope Mass Balance method for partitioning E and T: Isotopic mass balance method, IMB, firstly developed by [4] and recently improved by Li and Li (this volume) was used to separate E and T from total ET under field condition.

3. RESULTS

3.1. Isotope dynamics of soil water

3.1.1. Winter wheat season

Isotope values of soil water at different soil depths under different treatment fields are shown in Fig.1. Before winter (2009-11-05 and 2009-11-24), the values of δ^2H, $\delta^{18}O$ in 2.5 cm and 7.5 cm soil layers were much lower and nearly identical. The small evaporation caused by low temperature was the main reason for the difference. Comparing the values of δ^2H and $\delta^{18}O$ in soil deeper than 30 cm in the different treatments, it could be seen that there was no significant variation across the treatments for about 6 months. The reason for this was that both evaporation and root absorption of water happened higher than 30 cm. It could also be found that significant enrichment of δ^2H and $\delta^{18}O$ in the soil water in layer 0–2.5 cm on 7 April than that on 24 November, which could be attributed to the low surface evaporation and vapour movement from the deeper layers during winter. The rainfall on 18 May 2010 with isotopic values of –47‰ and –7.1‰ in δ^2H and $\delta^{18}O$, respectively, was much smaller than the value of the soil water in the surface layer on 22 May 2010. However on 13 June 2010, the rainfall water with –38‰ and –5.8‰ of δ^2H and $\delta^{18}O$, respectively, is nearly the same as the soil water. With strong evaporation between 22 May and 22 June, there was greater enrichment of ^2H and ^{18}O in soil water of the top layer.

3.1.2. Summer maize season

For summer maize growing during the rainfall season in July and August, the isotope values of soil water above 50 cm were very variable (Fig. 2), which was due to soil surface evaporation, crop transpiration, and frequent rainfall. The values of the isotopes of soil water below 50 cm were very stable across the whole season. It could be seen that there were two periods in which significant evaporation happened, 4 to 25 June, and 25 August to 29 September.

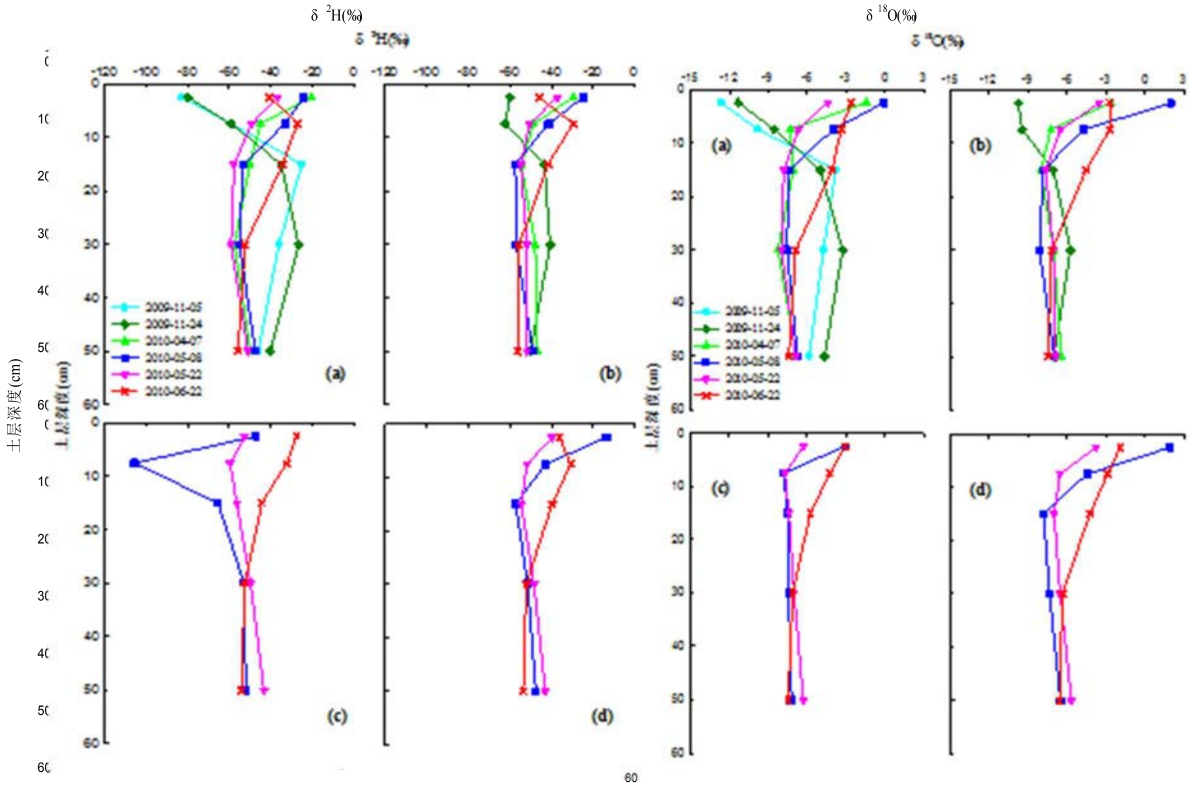

FIG. 1. The isotope of soil water in different treatments in the winter wheat field of 2010: (a) conventional treatment, (b) bare land formed before over-wintering, (c) plastic mulching treatment, (d) bare land formed after the reviving.

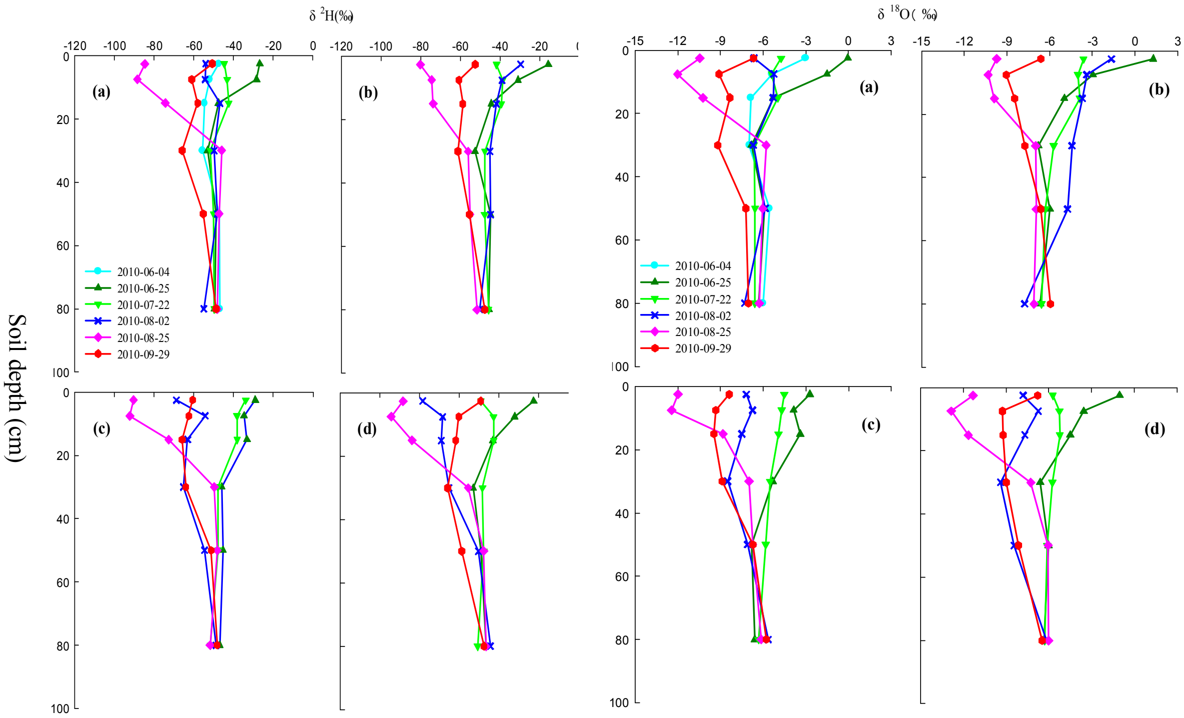

FIG. 2. The isotope value of soil water in different treatments in summer maize in 2010. (a) conventional treatment, (b)bare land, (c) plastic mulching treatment, (d) straw mulching treatment.

3.2. E and T calculated by water mass balance method

Water losses under different conditions calculated by the mass balance method were shown in Table 3. In the wheat experiment, (E+T) in control, 239.3 m^3/ha, could be well separated by E in bare soil, 105.9, and T in film, 123.4 in the whole growing season (Table 3). In the current work, crop transpiration accounts for about 52% of the total water loss in the winter wheat field. On the other hand, soil evaporation was the most important water loss pathway (88% of the total loss) in the last month of winter wheat season.

TABLE 3. WATER BALANCE IN THE WINTER WHEAT AND SUMMER MAIZE FIELDS IN 2010 (UNIT: MM)

Crop	Date (m/d)	Water input	Treatment	ET	E	T	Leaching	Water used
Winter wheat	4/7–6/22	198.5	bare	61.1	61.1	-	127.1*	188.2
			conventional	122.1	13.8	108.3	67.2*	189.3
Summe r maize	6/25–9/29	268.0	bare	74.8	74.8	-	154.2*	229.4
			conventional	206.1	0	206.1	85.4*	291.5

*calculated from the difference between the water consumption and ET

The amount and isotope composition of rainfall and irrigation water in the field experiment are shown in Table 4. It is important for the IMB method to obtain this information as accurately as possible.

TABLE 4. AMOUNT AND ISOTOPE COMPOSITION OF RAINFALL AND IRRIGATION WATERIN THE FIELD EXPERIMENT IN 2010

Water sources	Amount (mm)	δ^2H (‰)	$\delta^{18}O$ (‰)
Rainfall			
11 April	5.3	-60.63	-9.95
25 April	15.2	-56.87	-7.62
18 May	11.2	-47.39	-7.10
13 June	10.5	-37.78	-5.81
1 July	7.2	-37.05	-6.21
10 July	42.4	-34.64	-5.74
13 July	56.0	-47.93	-6.19
15 July	4.5	-39.37	-5.78
18 July	5.0	-66.69	-7.93
21 July	6.2	-69.36	-10.33
22 August	33.6	-97.38	-13.27
Total irrigation			
10 May	90	-62.55	-7.60

The result of the separation of E from ET by IMB and the soil water budget for the 0–60 cm depth soil for winter wheat and 0–100 cm for summer maize in 2010 are shown in Table 5 and winter wheat in 2012 in Table 6. It can be seen that IMB could detect well the E difference between the plots, just as we expected. For winter wheat, the E was about 22% of the ET under conventional method but 21% for filming, which means that filming in winter wheat could not reduce E significantly. For bare soil, E is approximately 40% of the ET, meaning that about 60% of the ET was seepage. On the other hand, filming and straw mulching could significantly reduce E in spring maize, by 19% and 7%, respectively.

TABLE 5. PARTITIONING EVAPORATION FROM EVAPOTRANSPIRATION IN WINTER WHEAT AND SUMMER MAIZE FIELD IN 2010 WITH IMB (UNIT: MM)

Crop	Conventional		Filming		Straw mulching		Bare	
	ET	E	ET	E	ET	E	ET	E
WW	147	33 (22)	92	19 (21)			56	23 (41)
SM	206	63 (31)	157	22 (12)	178	43 (24)	182	65 (38)

†Data in all brackets are the % of E in the ET. WW: winter wheat; SM: spring maize

The relatively smaller E for winter wheat (ca. 20%) can be attributed to delaying irrigation until the middle of May, when crop cover was nearly 100%. Before May, the top soil was very dry and E was inhibited. The E for summer maize (31%) can be assumed to occur during May to June, when crop cover was still low and there was no irrigation.

TABLE 6. PARTITIONING EVAPORATION FROM EVAPOTRANSPIRATION IN WINTER WHEAT FIELD IN 2012 WITH IMB (UNIT: MM)

Treatment	Date (m/d)	Δ soil water	irrigation	Rainfall	ET	E[1]	T[2]
Bare	4/2–5/9	–37.4	0	25.3	19.7	19.7	0
	5/9–5/30	+13.0	150	42.5	75.4	74.5	0
conventional	4/2–5/9	–8.3	0	25.3	33.6	10.3	23.3
	5/9–5/30	+16.9	150	42.5	175.6	0	175.6

1 calculated by IMB

2 obtained by the difference between ET and E

4. DISCUSSION

In the IMB method, three factors have important impacts on the result: the depth at which E occur, root depth, and soil temperature. Actually, it is difficult to find the real depth where soil water evaporates when the top soil layer is dry enough not to support evaporation happening. In the IMB method, the depth at which E occur is critical, as it determines how to calculate δ_l of soil water, which is used in the estimation of δ_e of the vapour. Results showed that, with different evaporation depths, the ratio of E to ET could be as much as 18% more and 44% less than the standard (Table 7), indicating the determination of the evaporation depth is important for a reasonable calculation with IMB method.

Root depth determines the δt in IMB method. Results showed that it could provide as much as 30% less than the standard situation (Table 7), which is less than the depth at which evaporation occurred.

We also can see in Table 7 that the effect of the soil temperature at 5 cm soil on E is not so important, only 2–3% difference when the temperature changed from 20℃ to 15℃, which is not likely to happen at a given location between different years.

TABLE 7. EFFECTS OF THE DEPTH OF EVAPORATION, ROOT DEPTH, AND SOIL TEMPERATURE AT –5CM ON THE EVAPORATION RATIO (%) CALCULATED BY IMB

Agronomic practice	Convention	Plastic Filming
E under Standard condition (mm)	33	19
E under different assumed evaporating depth (cm)		
0–5	31 (-6%)	22.5 (+18%)
0–10	23 (-30%)	14.5 (-24%)
0–20	18.5 (-44%)	11.5 (-41%)
E under different root depth (cm)		
5–60	26.5 (-21%)	17.5 (-8%)
5–40	24.5 (-25%)	16.5 (-13%)
20–60	23 (-30%)	16.5 (-13%)
E under different soil temp. at -5 cm (℃)		
20	24 (±2)*	16(±2)*
15	21 (±2)*	14(±2)*

Data in all brackets are the maximal difference of E from that of the standard condition.Standard condition: E occurring depth of 0–5 cm, root depth of 5–60 cm, and average temperature (at 5 cm of soil) of 20°C. *means the number in all brackets are the standard error of 6 cases.

The relatively large variation of E and T in this case study is the result of the long period, about 75 days. The longer the period, the more error is the isotope composition of soil water used for transpiration.

5. CONCLUSION

Results from IMB method showed that evaporation is about 20% of evapotranspiration in winter wheat field in North China Plain in conventional practice, whereas filming is about the same value. On the other hand, in summer maize, evaporation is much smaller in filming and straw mulching field than that in conventional field. Results of IMB can be used to measure difference in evaporation. However, evaporation ratio from IMB is greatly influenced by the assumed depths of evaporation in soil and water adsorption by roots.

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SPATIAL AND TEMPORAL VARIATION IN THE ISOTOPIC SIGNATURE OF TRANSPIRED WATER FROM A CONIFER FOREST CANOPY

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Abstract

Most conifer tree species have intrinsically low rates of leaf gas exchange and relatively high leaf water volumes. These traits establish low leaf-water turnover rates, which greatly extend the time required to achieve transpiration at isotopic steady state as environmental conditions change over diurnal periods. Canopy level variation in leaf physiology and microclimate contributes further uncertainty to the estimation of the isotopic composition of transpiration fluxes in forests dominated by conifers. Oxygen stable isotope ratios of water in needles of different age cohorts and from different canopy positions in subalpine fir (Abies lasiocarpa) were measured over a diurnal period during the growing season of 2008 in the Snowy Range of southeastern Wyoming, USA. Concurrent measurements of leaf gas exchange, canopy surface temperature, and the delta oxygen-18 ($\delta^{18}O$) and mixing ratio of water vapour within the canopy air allowed modelling of leaf water isotopic enrichment at sites of evaporation and the isotope ratio values of transpiration from different canopy positions. Leaf water achieved isotopic steady state with plant source water over only a brief period of the day in late afternoon, and $\delta^{18}O$ values of water from leaves lower in the canopy and from younger leaf cohorts were closer to those predicted from a steady-state model than those of older leaf cohorts and from higher in the canopy. The $\delta^{18}O$ value of transpired water differed by up to 10‰ from that of source water at midday in some parts of the canopy. Modelling the isotope composition of transpiration from conifer forest should take into account variation in leaf water turnover rates associated with differences in physiology and microclimate of needles of different age and from different canopy positions.

1. INTRODUCTION

Estimates of direct soil evaporation and plant transpiration are required to understand productivity responses of vegetation to inputs of irrigation or precipitation. Direct soil evaporation is a ‘nonproductive’ water loss, and management strategies focus on minimizing this loss in favour of ‘productive’ water usage through transpiration. Measurements of the stable isotope ratios of hydrogen (δ^2H) and oxygen ($\delta^{18}O$) in water are useful for tracing sources of evapotranspiration (ET) and partitioning transpiration (T) from direct soil evaporation (E) fluxes. Because E and T often have unique isotopic signatures, measurements of the isotope ratio composition in the atmospheric water vapour within the canopy boundary layer or in the residual soil water over time provide information on the sources of and processes controlling water exchange in the soil–plant–atmosphere system [1] [2].

Several approaches employing isotope measurements have been developed to estimate fractions of evaporation and transpiration in ET and their flux rates. Each approach has advantages and disadvantages related to the type of information provided (E/T fractions versus E and T fluxes), instrumentation costs, level of technical training required, the spatial and temporal scales of inference, and the number of assumptions and parameters requiring validation and estimation. These approaches are broadly defined as: (i) steady-state mixing approaches, including the 'Keeling plot' method [2], (ii) soil water isotope mass balance [3], (iii) the isotope flux gradient approach [4], and (iv) isotope mass balance calculations for canopy air [5]. The Keeling plot approach only provides information on the fractions of E and T in total ET, whereas the flux gradient and air mass balance approaches offer estimates of the flux rates of each of these components. Each approach involves varying levels of sophistication with respect to measurement and process-level understanding of isotopic fractionations that occur at the soil and leaf scale as water is released to the atmosphere and mixes with background air. Any of these approaches can be used in soil-plant-atmosphere transfer models to simulate and predict isotopic exchanges under varying conditions.

Using isotope measurements of atmospheric vapour to partition component fluxes requires accurate estimates of the isotope composition of plant-transpired water (δT). Spatial, temporal and species-level heterogeneity in δT makes this task challenging, and validation of leaf-level isotope fractionation models [6] are required. But discerning how rigorous one needs to be in accounting for fractionation processes and variation within canopies is dependent on the context of the study. Variation in leaf temperature, humidity and leaf-water turnover rates contribute to the complexity of δT within individual plant canopies. For example, it is often assumed in studies of leaf water isotopic enrichment that leaf temperature is closely coupled to air temperature. Yet this assumption may be invalid, especially where radiation loads and boundary layer resistances are high [7].

This study addresses how heterogeneity of gas exchange properties and microclimate of different leaves within a single complex canopy influence the isotopic signature of transpired water. Low rates of leaf gas exchange in some conifer species cause low leaf-water turnover rates, which greatly extend the time required to achieve transpiration at isotopic steady-state as environmental conditions change over diurnal periods [5][8]. Differences in stomatal conductance, transpiration and microclimate within the vertical profile of a conifer tree in a high-elevation environment with high radiation loads were investigated to understand the basis for variation in leaf water ^{18}O enrichment and its deviation from plant source water.

2. MATERIALS AND METHODS

The study was conducted at the Glacier Lakes Ecosystem Experiments Site (GLEES) (41°22.0′ N, 106°14.4′ W, 3190 m a.s.l.) in subalpine mixed conifer forest in southeastern Wyoming, United States [9]. The oxygen stable isotope ratio ($\delta^{18}O$) of water was measured in leaves of different ages and from different vertical canopy positions in a subalpine fir (Abies lasiocarpa) tree over a diurnal period during the growing season of 2008. Needles were collected every 3–4 hour (h) over a 24 h period to investigate the rapid changes in leaf-water isotopic enrichment. Concurrent measurements of leaf gas exchange, humidity and temperature allowed estimation of the isotope ratio of transpiration from the different canopy positions and investigation of the deviation of leaf water $\delta^{18}O$ values from isotopic steady state.

2.1. Leaf sampling, gas exchange and canopy temperature measurements

Needles were collected from an A. lasiocarpa tree growing adjacent to a tall (30 m) scaffold. The scaffold, used to support instrumentation for the GLEES Ameriflux measurements, allowed easy access to the canopy without major disturbance to the tree. Needles were sampled from 9.5, 13.7 and 17 m above ground surface on the approximately 20 m tall tree every 3–4 h (seven times in total) over 24 h beginning at 08:00 h on day-of-year 213 (31 July), 2008. Needles were collected separately from the current year's growth and from one and three year old needle cohorts at each canopy position and time period. Approximately 30–40 needles were removed from twigs for each sample and sealed in screw-cap glass vials. Stems were collected during the mid-day period for plant source water isotope analysis. Small twigs were collected from each canopy position, separated from attached needles and placed also in screw-cap glass vials. Vials were covered with parafilm and stored in a freezer at –2°C until water extraction (described below).

Stomatal conductance and transpiration of needles in each cohort and canopy position were measured during the same seven time periods used for needle collection. Gas exchange measurements were made using a LiCor 6400 with a standard leaf cuvette and with all environmental conditions (cuvette temperature, light level, humidity) set to match ambient conditions. A hand-held infrared thermometer was used to monitor needle temperature at each canopy height.

2.2. Canopy air water vapour sampling

Atmospheric water vapour was collected at each of the three canopy positions used for gas exchange measurements and needle collection, employing an automated sample profiler that routed air from each height through low-absorption Bev-a-Line IV tubing to Pyrex glass traps [10] held at –80°C in an ethanol bath. The air stream from each position in the canopy was diverted frequently through an infrared gas analyzer (LI 840, LiCor, Inc.) for measurement of air water-vapour mixing ratio. The sampling system is thoroughly described by [11] and [12]. For the current study, water vapour was trapped in air at a flow rate of 300 ml/min for 30 min during each of the seven sampling periods at each of the three heights in the canopy.

2.3. Water extraction and stable isotope analysis

Water from needle and stem samples was retrieved using cryogenic vacuum distillation [12]. Complete quantitative extraction was verified from weight measurements performed before and after cryogenic extraction and then again after oven drying. Extraction efficiency was better than 95 percent for all samples. The $\delta^{18}O$ values of stem, needle and atmospheric water samples were determined by the CO_2 equilibration technique using a Gas Bench II coupled to a Thermo Delta Plus XP Isotope Ratio Mass Spectrometer (Thermo Scientific Corporation, Bremen, Germany) at the University of Wyoming Stable Isotope Facility. Measured $\delta^{18}O$ values were linearly corrected to the V-SMOW international scale using two calibrated laboratory standards that were analysed with each batch of unknowns along with a QA/QC standard. Precision of repeated analysis of the laboratory QA/QC standard was better than 0.2‰.

2.4. Steady state leaf water isotope model

Measured $\delta^{18}O$ values of water extracted from needles were compared with values predicted by a Craig and Gordon steady-state model adapted for leaves [13]:

$$\delta^{18}O_e = \delta^{18}O_s + \delta^* + \delta_k + (\delta^{18}O_v - \delta^{18}O_s - \delta_k)\ e_a/e_i \qquad (1)$$

where $\delta^{18}Os$ = the oxygen isotope ratio of plant source water; $\delta^{18}Ov$ = the oxygen isotope ratio of atmospheric water vapour; δ^* = the temperature-dependent equilibrium fractionation factor [14]; δk = the kinetic fractionation factor during diffusion through the stomata and boundary layer; and ea/ei is the ratio of ambient to intercellular vapour pressure.

The δk value is dependent on the proportion of diffusion resistance through the stomatal pores (rs) and boundary layer (rb) [15] [16] and is calculated by:

$$\delta_k = (32r_s + 21r_b)/(r_s + r_b) \qquad (2)$$

The $\delta^{18}O$ value of water in leaves predicted by Equation 1 is that for sites of evaporation, and not for the bulk leaf water. To estimate the $\delta^{18}O$ value of bulk leaf water at isotopic steady state ($\delta^{18}O_L$), a model was employed that accounts for the back diffusion and mixing of ^{18}O enriched water at sites of evaporation with un-enriched source water from leaf veins:

$$\delta^{18}O_L = \delta^{18}O_s + (\delta^{18}O_e - \delta^{18}O_s)(1 - e^{-P})/P \qquad (3)$$

where P is the Péclet number. P is calculated as EL/CD, where: E = transpiration rate ($mol/m^2/s$); L = the effective path length (taken as 0.008 m); C = the molar density of water ($55.5 \times 10^3\ mol/m^3$); and D = the diffusivity of $H_2{}^{18}O$ in water ($2.66 \times 10^{-9}\ m^2/s$) [13].

3. RESULTS AND DISCUSSION

Needle temperature differed substantially from air temperature during daytime and nighttime periods (Fig. 1). The largest difference was observed for needles in the upper canopy exposed to high radiation, where needle temperature was as much as 6.5°C higher than air temperature in mid-afternoon. Radiative cooling of the canopy during night time caused needle temperatures to drop below air temperature by as much as 4.5°C. Despite the high wind speeds common at this forest site, the simple assumption of close coupling of leaf and air temperature would lead to substantial error in modelling leaf water ^{18}O enrichment. For example, a 6.5°C difference in needle temperature from 15 to 21.5°C would produce a 0.6‰ difference in δ^* (Eq. 1). The assumption also would introduce error in the calculation of e_a/e_i; at 15°C air temperature and 50 percent air humidity, e_a/e_i would be 0.35 assuming equal leaf and air temperature and 0.5 with a 6.5°C higher value of leaf temperature.

The hot and dry conditions in the afternoon period reduced stomatal conductance and transpiration, especially in upper parts of the tree canopy (Fig. 2). Low hydraulic conductivity in the xylem of stems caused by bark beetle transmission of a fungal pathogen may have substantially limited the rates of transpiration from the upper canopy in this plant. Leaf longevity is also quite high (ca. 6–10 years) in this species and stomatal conductance and transpiration rates tend to decline as leaves age in conifers. Indeed, stomatal conductance was higher in the youngest needle cohort compared to the 1and three year old cohorts (data not shown) in the current study. Values of stomatal conductance and transpiration were used to estimate leaf water ^{18}O enrichment using Equations 1–3 for comparison against measured values. Differences in leaf gas exchange properties among the three different aged needle cohorts and at the different canopy heights were sufficient to cause substantial variation in leaf water ^{18}O enrichment within the A. lasiocarpa canopy that translated into variation in the $\delta^{18}O$ value of leaf-transpired water vapour.

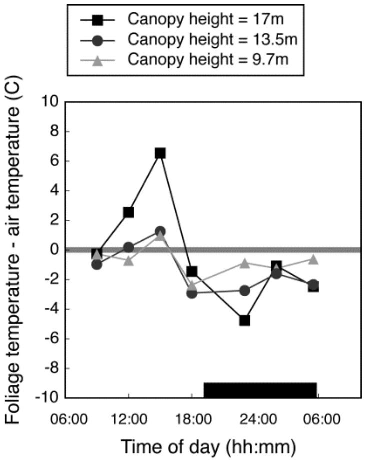

FIG. 1. Difference between foliage (needle) temperature and surrounding air temperature in the canopy of A. lasiocarpa. Note: the bar in the figure indicated measurements during a 12-hour period from 6 pm to 6 am.

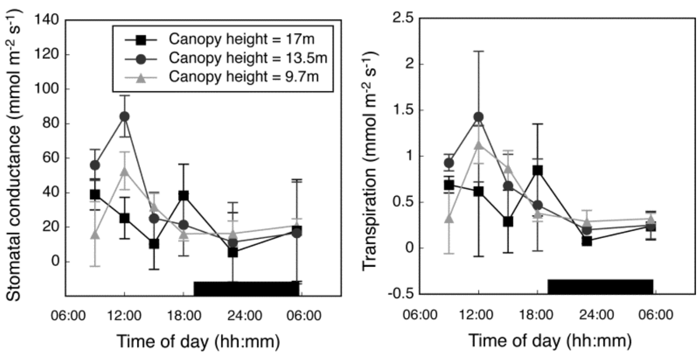

FIG. 2. Stomatal conductance and transpiration at different canopy heights of A. lasiocarpa.

Overall, the generally low rates of leaf-level T (and consequentially low leaf water turnover rates) in the A. lasiocarpa in this study did not allow $\delta^{18}O$ values of needle water to achieve steady state with environmental conditions (Fig. 3). However, leaves lower in the canopy compared to those higher in the canopy were closer in their $\delta^{18}O$ values as predicted by the Craig and Gordon steady-state model.

Bulk leaf water $\delta^{18}O$ values were used to calculate leaf transpiration $\delta^{18}O$ values. These values, reported by canopy height and by leaf age cohort, were different than tree source water $\delta^{18}O$ values over much of the diurnal period (Fig. 4), indicating the importance of considering isotopic non-steady state T in ET partitioning studies.

The dynamics of leaf water ^{18}O enrichment and the $\delta^{18}O$ value of transpired water in needles of subalpine fir (A. lasiocarpa) are poorly represented by a simple isotopic steady state model, and deviations are systematically related to canopy position and leaf age. It is often assumed that transpiration isotopic composition can be estimated simply from measurements of plant xylem or leaf water, this study concluded that modelling the isotope composition of forest T and leaf water to increase predictive understanding of ET should take into account the variation in leaf water turnover rates associated with variation in physiological properties of needles of different ages and canopy position that affect isotopic non-steady state T values. To predict short-term changes in the isotope composition of water vapour in forest canopy air (e.g. [5]), models should account also for the potential differences between leaf and air temperature that drive equilibrium and kinetic fractionations.

4. CONCLUSIONS

Leaf and air temperatures in the upper canopy were not in equilibrium. Assumptions of leaf-air temperature equilibrium in models of leaf water ^{18}O enrichment may lead to substantial error. Stomatal closure during hot, dry afternoon periods reduced transpiration, especially in the upper part of the canopy, which altered leaf water ^{18}O enrichment relative to that predicted by the steady state model. Calculated $\delta^{18}O$ values of leaf transpired water deviated substantially from tree source water values across all canopy heights, but less so in young compared to older needles. Dynamics of leaf water ^{18}O enrichment and the $\delta^{18}O$ value of transpired water in subalpine fir is very poorly represented by a simple isotopic steady state model, and deviations are systematically related to canopy position and leaf age.

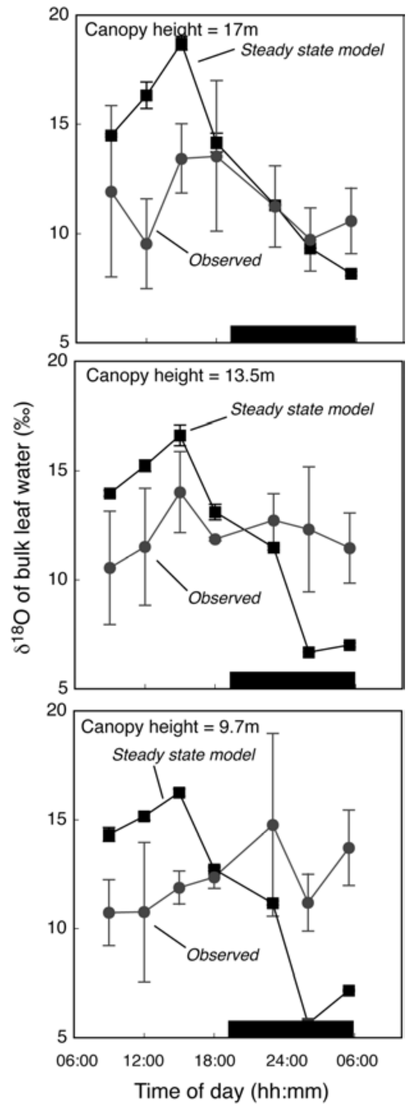

FIG. 3. The observed and predicted $\delta^{18}O$ value of bulk leaf water at different canopy heights.

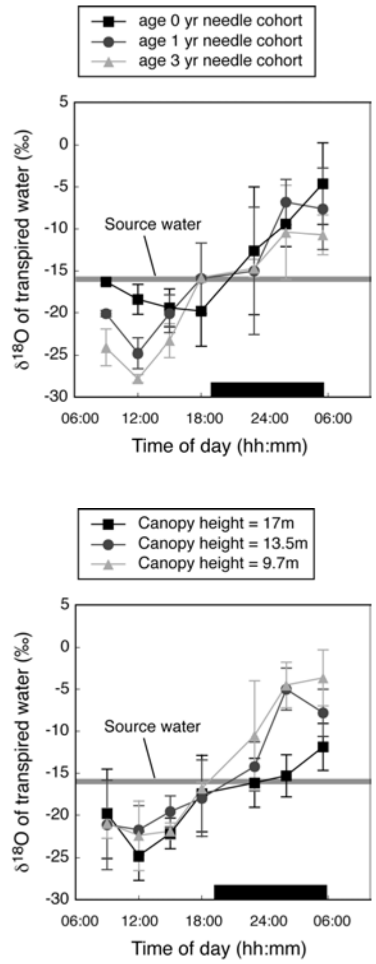

FIG. 4. The $\delta^{18}O$ value of leaf transpired water in A. lasiocarpa calculated from bulk leaf $\delta^{18}O$ values.

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EVALUATION OF EVAPOTRANSPIRATION AND PRODUCTION OF PAPRIKA (CAPSICUM ANNUM L.) USING THE SOIL WATER BALANCE APPROACH UNDER VARIABLE IRRIGATION WATER APPLICATIONS[1]

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Abstract

An experiment was conducted at the Research Field Station at the University of Zambia, Lusaka on a high-value crop using small-scale drip irrigation system to maximize water use efficiency by determining the soil evaporation (E) and transpiration (T) components. Precise estimation of evapotranspiration (ET) for the different growth stages is important for the field soil water balance and to determine irrigation requirements. A randomized complete block design experiment with four replications and four water application rates of 50%, 75%, 100% and 100% with plastic of ETc evapotranspiration rates was carried out. Paprika (Capsicum Annum L.) was used as the test crop. To determine transpiration, soil water was monitored with soil moisture neutron probe to 150 cm depth over the season; green canopy cover was also regularly monitored using images taken using digital camera. The partitioning of ET into E and T was obtained using canopy cover values which was then converted to leaf area index (L) through the equation E=ETexp(-0.61L). The result showed that the component of transpiration was negligible during the first 25 days after transplanting (DAT) and thereafter the component started to increase exponentially. Transpiration estimates over the season varied from 38 mm to 70 mm, resulting in an average value of 59 mm. Transpiration from the plastic cover treatment was 5 mm lower, with most of the water loss through evaporation during plant establishment before the plastic cover was installed. Generally, during the vegetative stage 75% of ET was E while the remaining 25% was lost through T. The results on biomass production measured during the vegetative growth showed that the higher the amount of water applied, the higher was the amount of biomass produced. This indicated the detriminal effect of water stress affecting biomass production and the final yield obtained. However, the water use efficiency (biomass per unit ET) was highest under 50% ET and lowest in the 75% treatment (6 kg/ha/mm versus 5.1 kg/ha/mm).

1. INTRODUCTION

Low-head drip irrigation systems are being promoted for the production of high value crops in order to mitigate impacts of drought in southern Africa, and to ensure efficient resource utilization and food security at household level. It is a low cost system that attempts to retain the benefits of conventional irrigation systems whilst removing factors preventing their uptake by resource-poor, smallholder farmers such as purchase cost, the requirement of a

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pressurized supply, the associated pumping costs and the complexity of operation and maintenance. These systems are usually sold in kit form for relatively small areas of land (25 square meters) to keep the cost down and giving room for incremental development not easily accomplished with normal commercial systems. Most smallholder farmers in southern Africa and Zambia in particular rely heavily on rainfed agriculture and are frequently faced with drought that affects their crop production. Low-cost, low pressure drip irrigation are being introduced to mitigate against drought and ensure food and income security. With the recent introduction and promotion of the low-cost drip system in southern Africa and Zambia in particular, it is proposed to evaluate the system in Lusaka as part of a concerted effort to understand water dynamics in the root zone of paprika (Capsicum Annum L.) under local conditions.

Paprika (Capsicum annuum L.) is an indeterminate plant and is a high value cash crop commercially cultivated under both rainfed and irrigated conditions in arid and semi-arid environments [1]. It is used as a vegetable and consumed both as fresh and dehydrated spice [2]. The total world production of paprika is estimated at 14 to 15 million tons a year [3]. Consequently, its cultivation worldwide signifies the commercial importance of paprika [4]. In horticulture, paprika is considered one of the most susceptible crops to water stress [5], hence its cultivation is limited to warm and semi-arid environments. Such sensitivity has been documented in several reports that studied the yield reductions effected by water stress [6], [7]. The flowering and fruit development phases are considered to be most sensitive to water deficits [8].

Evapotranspiration is a major component of the water balance of natural and managed ecosystems and accounting for more than 80% of partitioned precipitation inputs into ecosystems [9]. In water-limited ecosystems, partitioning of ET between plant transpiration and soil evaporation remains a theoretical and technical challenge. However, some common methodologies exist that include use of individual-tree sap flux [10], soil water balance [11], soil lysimeters [12]; time series of soil surface temperature [13], models and remote sensing [14], micrometeorological techniques [15], and stable isotopic tracer analysis [16], each of these methods has limitations. The isotopic technique is based on the isotopic composition of transpiration (δT) which is different from the isotopic composition of evaporation (δE) [17]; the corresponding distinct isotopic signature of these two fluxes can be used to partition total ET into relative rates of evaporation and transpiration. In this study, we applied green canopy measurements and use the approach of [11] to partition evapotranspiration calculated from the root-zone soil water balance to estimate the fraction of transpiration as the crop establishes. Precise estimation of evapotranspiration for the different growth stages is of importance for the field water cycle and to determine irrigation requirements that are usually estimated from the Penman-Monteith equation.

The study was part of the regional initiative to: i) Quantify and develop means to manage soil evaporative losses to maximize the beneficial use of water; ii) Quantify, and develop means to improve the amount of biomass produced per unit of transpiration; and iii) Devise irrigation and related management techniques to enhance the yield component of biomass production.

2. EXPERIMENTAL DESIGN

The field experiment was conducted at the University of Zambia Agriculture Field Station in Lusaka, Zambia (lat: 15°23″ S, long: 28°20″ E Alt: 1262 m asl). According to Koeppen Climatic classification, the site falls under a warm temperate zone with a dry winter and a hot summer. The average daily maximum and minimum temperatures are 25°C and 15°C, respectively. The average rainfall varies from 800 mm to 1 200 mm with an estimated precipitation deficit of 647 mm per annum (Fig. 1). The length of the rainy season is about 140 days (November–March) while the dry season is estimated at 225 days. The long season with cool temperatures at the beginning and later culminating in warmer temperatures makes it possible to grow a number of irrigated crops.

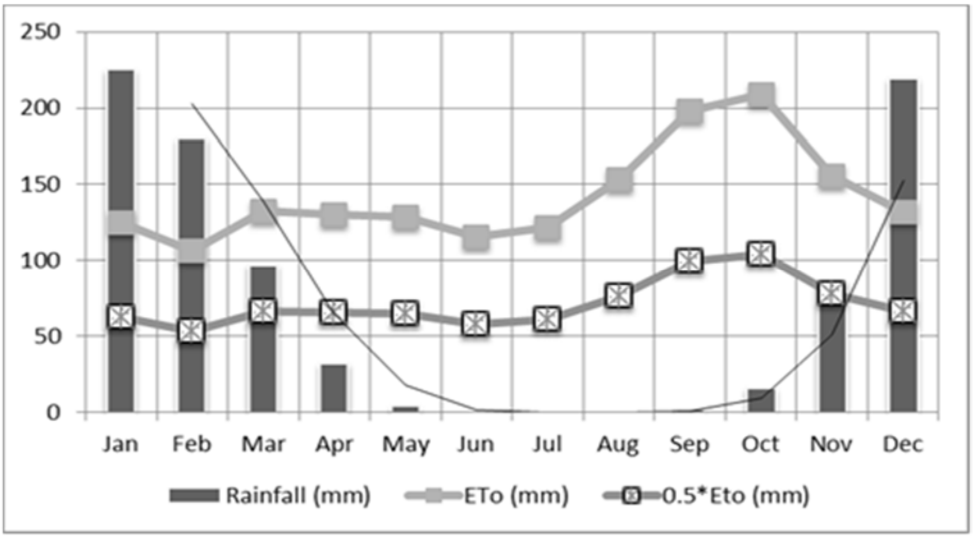

FIG. 1. Long-term average monthly precipitation and evapotranspiration.

The experimental design is a complete block design with four replicates and four treatments (water application rates of 50%, 75%, 100% and 100% with plastic of ETc). Water was supplied through a metered drip irrigation water supply system. Each plot was equipped for: i) soil water profile measurements using a neutron moisture (CPN); ii) water application through drip irrigation; iii) biomass measurements; and iv) weather data monitored with an automatic weather station (Fig. 2). Evapotranspiration was calculated from a root-zone soil water balance approach and partitioned into E and T using crop green canopy estimates from digital camera pictures [18].


A


B

FIG. 2. Illustration of the drip system (A) and weather station (B) at the experimental site.

Paprika seedlings (Capsicum Annum L.), cultivar ‘Queen’ 5-week old were transplanted at a an inter-row spacing of 0.90 m and between plants along drip lateral lines of 0.75 m. A portable sprinkler irrigation system was used to irrigate the plants twice at 3 and 14 days after transplanting (DAT) until 37 DAT, with 30 mm of water to ensure plant establishment. Subsequently, drip irrigation was applied every two days, with exceptions of days when rainfall was received, with each drip line for every two rows and emitters spaced 0.30 m apart. The plants also received basal fertilizer at a rate of 300 kg/ha (NPK: 10-20-10) and split top dressing fertilizer application at 300 kg/ha (NH_4NO_3). Above-ground biomass was estimated from plant girth diameter measurement 4 times during the experiment on DAT 29 and 63. They were oven-dried for at least 48 h at 70°C, with dry weight of the samples separated from leaf, stem and fruit Green canopy cover was estimated from digitising canopy pictures using software Green Crop Tracker [18].

2.1. Soil type

The soil at the site is a deep, dark brown to yellowish red, well drained clay loam with a loam textured surface layer and clay textured subsurface layers derived from quartzite and classified as a Paleustalf [19]. The bulk density was uniform within the range 1.5 to 1.6 g/cm^3 which may be attributed to the clay and silt contents. The characteristics of the soil physical and chemical properties are presented in Table 1. The water content at field capacity varied from 28% to 32% while wilting point varied from 8% in the surface soil to 13% in the sub-soil on a volumetric basis. The available water holding capacity varied from 0.173 to 0.202 mm mm^{-1}. The soil chemical properties (Table 2) showed a low nutrient level; hence fertilizer application is required for stabilizing and improving crop productivity.

For the parameterization of the soil hydraulic functions, the water retention, θ(h), and hydraulic conductivity, K(θ), curves were described according to the Mualem–van Genuchten [20] functions based on a capillary network model of the pore size distribution [21]. The parameters of these functions were derived from soil water retention curves measured on undisturbed core soil samples (100 cm^3) collected from a representative soil profile. Similarly the saturated hydraulic conductivity (Ks) was derived from inverse modelling of cumulative infiltration measurements from undisturbed core samples using mini disc infiltrometers (Decagon). The results on the hydraulic properties are presented in Table 3. The saturated hydraulic conductivity (Ks) was within the range of 40 to 60 mm d^{-1} indicating that the soil was slow-draining. This is attributed to the high clay content of the soil profile (>30%).

TABLE 1. SOIL PHYSICAL PROPERTIES, BULK DENSITY (ρ_b), TEXTURE AND WATER RETENTION CHARACTERISTICS OF A REPRESENTATIVE SOIL PROFILE AT THE SITE

Soil depth (cm)	ρ_b (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)	Textural class (USDA)	FC (v v^{-1})	WP (v v^{-1})	AWC (mm/m)
0–20	1.58	42	32	26	Loam	0.280	0.078	202
20–45	1.57	24	34	42	Clay	0.297	0.124	173
45–80	1.56	28	32	40	Clay	0.303	0.126	177
80–120	1.53	22	34	44	Clay	0.313	0.132	181

†FC = field capacity, WP = wilting point, AWC = available water-holding capacity, ρ_b = bulk density

TABLE 2. SOIL CHEMICAL PROPERTIES OF A REPRESENTATIVE SOIL PROFILE AT THE SITE

Soil depth	pH ($CaCl_2$)	OM	P	K	Ca	Mg	Na	B	eCEC	BS
(cm)		(%)	(mg/kg)	<-----------(meq/100g)-------->				(mg/kg)	(cmol$^{(+)}$/kg clay)	
0–20	7.3	2.1	15.1	0.1	5.2	0.8	0.03	0.06	23.29	100
20–45	6.8	1.5	2.4	0.2	4.5	0.9	0.04	Trace	13.28	98
45–80	7.1	1.5	2.5	0.2	3.8	0.9	0.03	Trace	12.13	100
80–120	7.3	0.6	1.7	0.2	4.5	1.2	0.04	Trace	13.22	100

TABLE 3. SOIL HYDRAULIC PROPERTIES OF A REPRESENTATIVE SOIL PROFILE AT THE SITE

Soil depth (cm)	θs (v/v)	θr (v/v)	α	n (/cm)	m	Ks (mm/d)
0–20	0.379	0.065	0.0147	1.3751	0.2728	55.4
20–45	0.410	0.085	0.0142	1.3183	0.2414	41.4
45–80	0.409	0.083	0.0145	1.3228	0.2440	45.0
80–120	0.424	0.088	0.0143	1.3240	0.2447	51.8

†θs and θr (cm^3/cm^3) are saturated and residual water content, α (/kPa), n and m (m = 1 – 1/n) are empirical parameters and Ks (cm/min) is the saturated hydraulic conductivity

2.2. Irrigation scheduling

The irrigation schedule was developed from the historical weather data for the experimental site. The crop's actual evapotranspiration (ETc) was estimated from the reference evapotranspiration (ETo) using the Penman-Monteith equation [22] corrected by the crop coefficient (Kc) for pepper (Table 4). Three treatments of irrigation were carried out: 100, 75 and 50% ETc.

TABLE 4. DAILY REFERENCE EVAPOTRANSPIRATION (ETo), CROP COEFFICIENT (Kc) AND CROP EVAPOTRANSPIRATION (ETc) AVERAGED OVER THE GROWTH STAGES USED FOR IRRIGATION SCHEDULING

Irrigation Treatment	Growth Stage (days)	ET_0 (mm/d)	Kc	ETc (mm/d)
100%	00-24 DAP	5.55	0.73	4.07
	25-58 DAP	6.70	0.82	5.51
	59-91 DAP	6.31	0.90	5.69
	92-107 DAP	4.89	0.88	4.29
75%	00-24 DAP	4.16	0.55	3.05
	25-58 DAP	5.02	0.62	4.13
	59-91 DAP	4.73	0.68	4.27
	92-107 DAP	3.67	0.66	3.22
50%	00-24 DAP	2.78	0.37	2.04
	25-58 DAP	3.35	0.41	2.75
	59-91 DAP	3.15	0.45	2.85
	92-107 DAP	2.45	0.44	2.14

2.3. Soil water measurements

Soil water content measurement was carried out using a neutron moisture meter (CPN) to a depth of 1.5 m, at a depth interval of 0.15 m. PVC pipe access tubes was used; they were installed in the centre of the drip lines. The neutron moisture meter was calibrated during the study within and around the experimental plots. The measured soil water content was transformed to hydraulic head profiles using previous soil water retention functions developed by desorption experiments from undisturbed core soil samples using standard techniques [23], [24], to enable root zone soil water balance and drainage calculations. A gravimetric method was applied to measure soil water content at the beginning of the experiment and during the main growth stages. The RETC software [20, 25] was used to estimate soil hydraulic parameters from the moisture retention data.

2.4. Root-zone soil water balance

the paprika soil water balance was used to evaluate evapotranspiration, by accounting for all water additions and subtractions from the soil root zone, and determining soil water deficit and irrigation scheduling. The biggest (>90%) subtraction of water from the root zone comes from crop water uptake or evapotranspiration. On the other hand precipitation and irrigation provide the major additions. The soil water balance equation integrated over daily periods ($\Delta t = ti + 1 - ti$) can be represented by:

$$(P + I) - (Q + ET) = \Delta S \quad (1)$$

where P is rainfall (mm); I is irrigation (mm); ET is crop evapotranspiration (mm); ΔS is soil water storage changes (mm) and Q is drainage soil water fluxes below the root-zone (z), all during periods ti and ti + 1, i being the time index.

Solving for the crop evapotranspiration, the above equation becomes:

$$ET = (P + I) - (Q + \Delta S) \quad (2)$$

The root-zone soil water balance was used to estimate the actual crop evapotranspiration (ETc). Soil water fluxes below the root zone were calculated using Darcy's equation:

$$Q = -K_{(\theta v)} * \left.\frac{dH}{dz}\right|_{z} * \Delta t \quad (3)$$

where K(θ) is the unsaturated hydraulic conductivity as a function of the volumetric water content (θV) and dH/dz is the hydraulic head gradient. The changes in root-zone soil water storage (ΔS) during a given time interval (Δt = t2 – t1) were calculated from the integral of measured soil moisture profiles:

$$\Delta S_{(0,z)} = \int_{t_1}^{t_2} \int_{0}^{z} \theta . dz \quad (4)$$

2.5. Statistical analysis

A Completely Randomized Block Design (CRBD) was used, with four treatments and four replications. GenStat was used to analyse the data. Means were compared by Least Square Difference Test (LSD) at 5% level of confidence.

3. RESULTS AND DISCUSSION

3.1. Weather data

The total amount of water received through irrigation and rainfall in 2011–2012 is given in Fig. 3. A total of 194 mm of rain fell during the growing period, with the majority occurring during the latter part of the season.

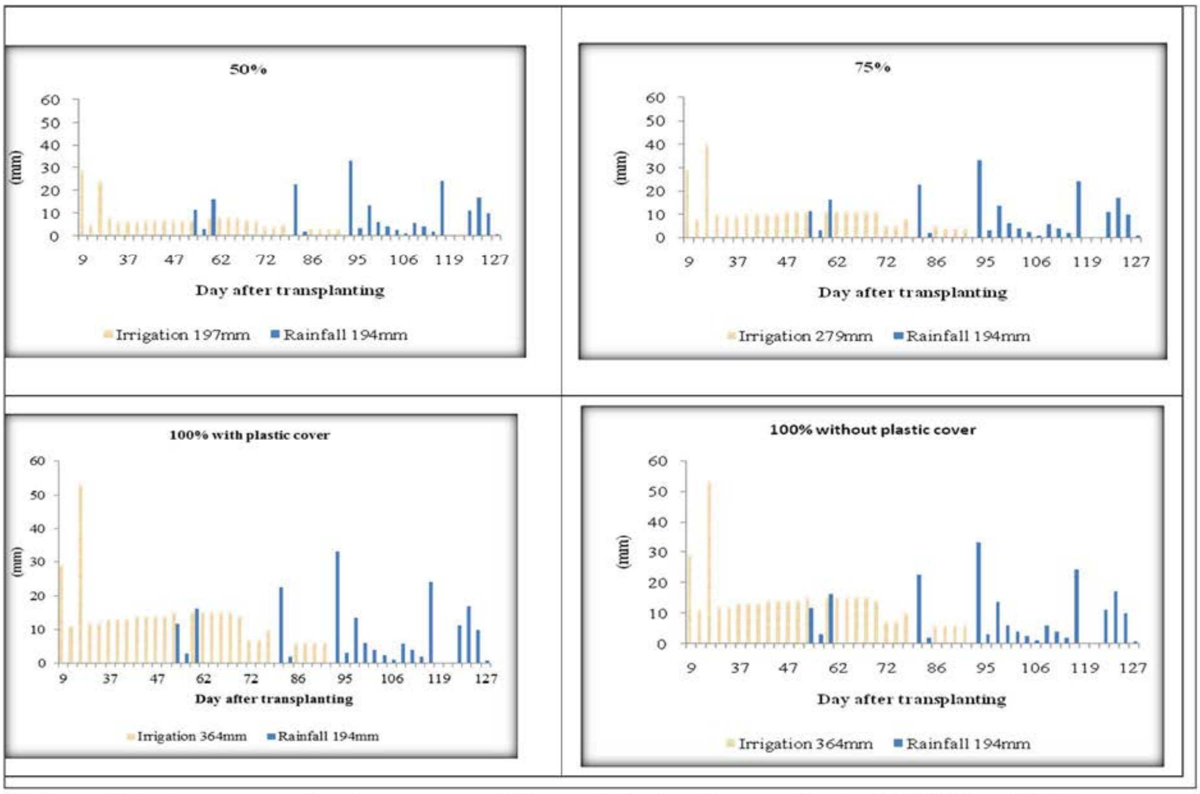

FIG. 3. Total amount of water received through irrigation and rainfall (2011–2012).

Fig. 4 presents part of the weather data for the study site. The maximum temperature during the period varied from 21°C to 35°C while the minimum temperature varied from 3°C to 22°C. These low temperatures could have affected the growth of the crop, however the temperature kept on increasing as the growing season continued. The vigorous plant growth was observed as temperatures increased during the observation period. Comprehensive weather data during the study period are presented in the appendix. It is worth noting that during the same period the site received 11.2 and 16.8 mm rainfall which was equivalent to 3 and 4 days of irrigation interval.

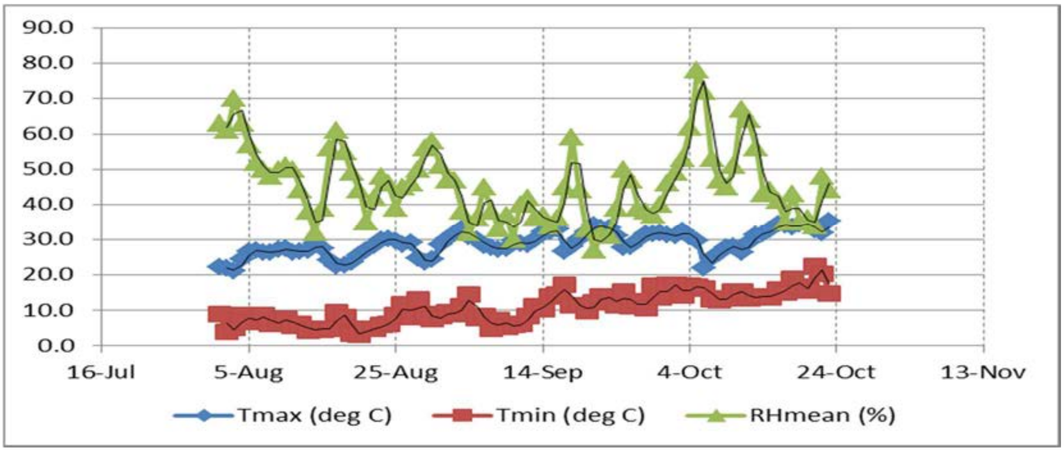

FIG. 4. Air temperature and relative humidity during the growing season.

3.2. Soil water profiles

3.2.1. Variation of soil moisture profiles extreme wet and dry days

The results on the lower and upper limits of the soil moisture in the profile during the vegetative stage of the paprika crop are presented in Fig. 5. Except for the surface layer the moisture content was close to 30%, a value within the range of the field capacity of the soils of experimental site (varied from 28% to 32% on volume basis). The results therefore indicated that the field capacity (upper limit) was achieved during the irrigation cycles. The lower limit (wilting point) for this soil was in the range 7% in the top soil to 14% for the sub-soil. From Fig. 4, it was observed that soil moisture in the profile was always higher than the lower limit in all treatments.

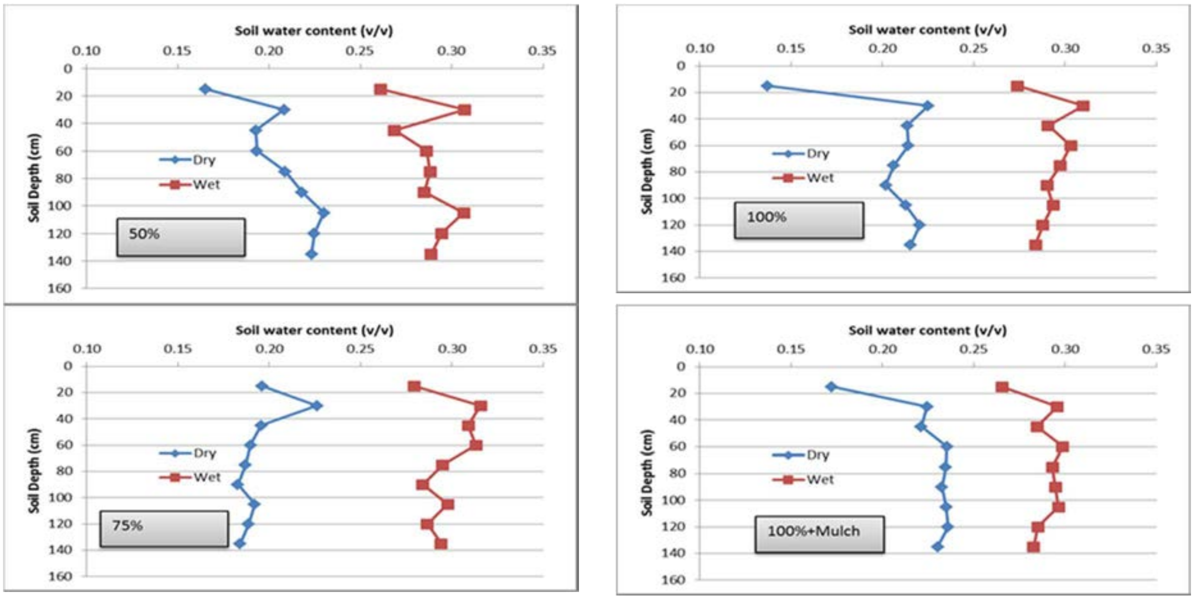

FIG. 5. Extreme values of dryness and wetness for the soil moisture profiles during the crop growth.

Fig. 6 presents the results for the mean soil moisture profile for the four irrigation regimes which indicate that the soil moisture was maintained close to 25% with the exception of the surface soil during the vegetative period. The lower moisture content at the surface is associated with combined processes of evaporation and transpiration which occurred during the growth stage. The reduced differences between the initial and final soil moisture profile under the 75% treatment was attributed to the fact that two of the plots had a higher clay content which was influenced by the presence of anthills.

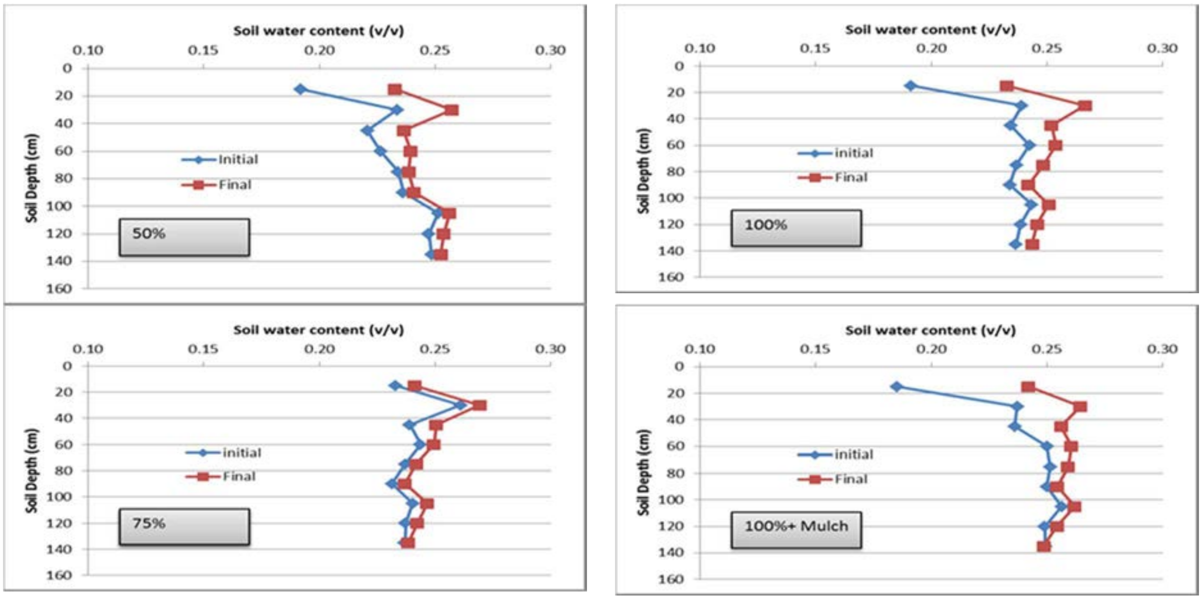

FIG. 6. Soil moisture profiles during initial and final vegetative growth for the four treatments.

3.2.2. Evolution of soil moisture in the root-zone during the vegetative growth stage

The changes in soil moisture at different soil depths over the cropping season as affected by the rate of irrigation application are presented in Fig. 7. No significant differences were observed in the soil moisture content as affected by the rate of irrigation application during the vegetative growth stage of the crop. This may be attributed to the dominance of evaporation process during this period as the crop was getting established. It is expected that as the crop grows towards flowering and fruit formation the increased demand for water would be noticed in the data. The general increase in soil water content in late September was due to the rainfall which was received and to some extent cancelled treatment effects. However the same rainfall was equivalent to 10 days of irrigation hence no irrigation was applied during this period.

3.2.3. Components of the soil water balance

Components of the root-zone water balance during the vegetative growth are presented in Table 5 and Fig. 8. There were no significant differences in the amount of drainage (Q) and changes in soil water storage (ΔS) in the root-zone. This could be attributed to the high CVs (>50%), however there were differences in the total crop evapotranspiration (ETc) with the highest observed under the 100% treatment. In the 100%+ mulch (plastic cover) treatment, the predominant evaporation (E) occurred during seedling establishment, i.e. before the plastic cover was introduced to the soil surface. It is expected that soil evaporation will be zero upon covering the surface with a plastic cover.

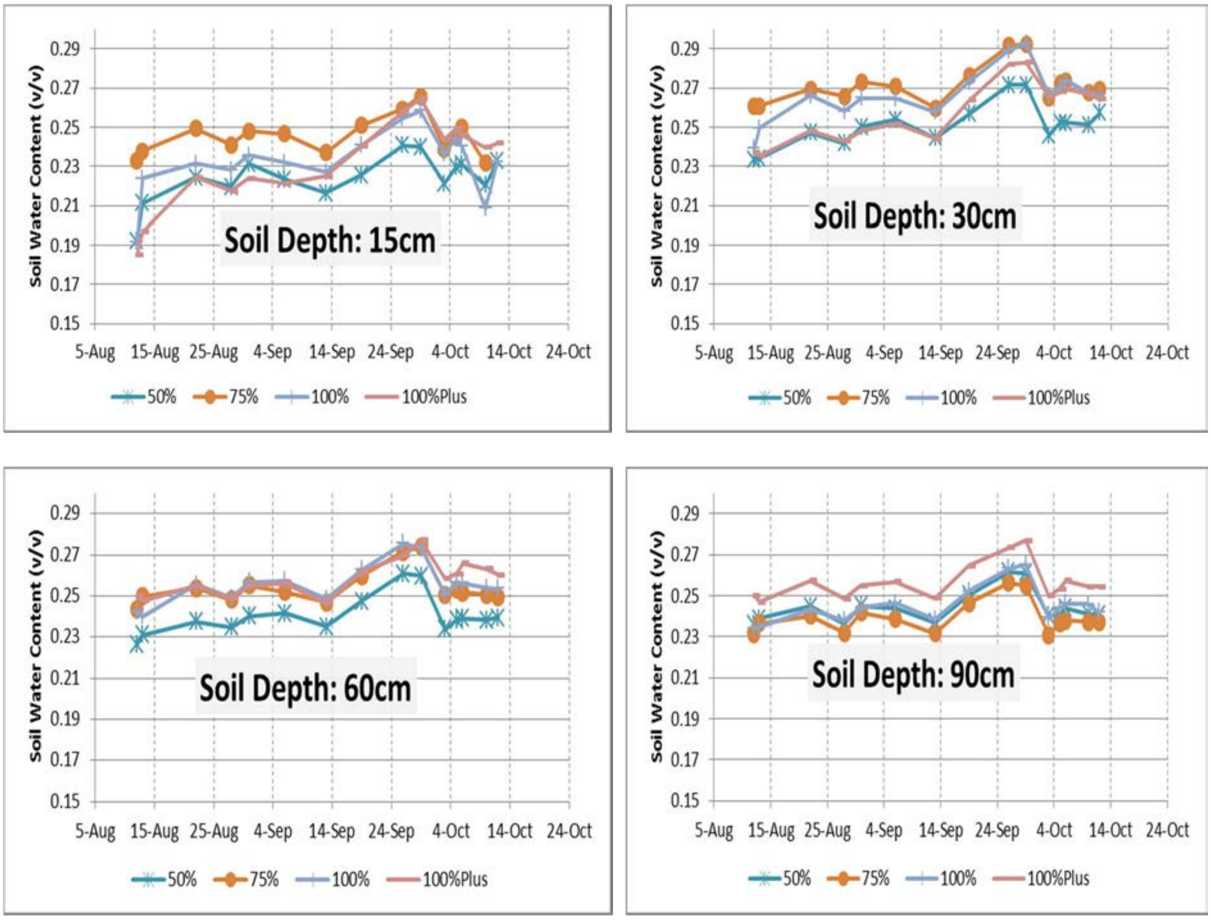

FIG. 7. Effect of irrigation rate on soil moisture at selected soil depths.

Generally the changes in soil water storage (ΔS) and drainage (Q) were positive, showing that treatments did lead to an increase of soil moisture in the root-zone (Fig. 8). This could be attributed to the low crop water requirement during this period of vegetative growth. Soil water balance carried out indicated that during the vegetative growth of the paprika crop, the water supplied to the root-zone was partitioned into crop evapotranspiration (ETc) (78%), drainage (6%) and change in soil water storage (16%). No significant differences were observed in the treatment on drainage and soil water storage changes except for ETc which was significantly ($P<0.001$) lower under the 50% treatment compared with other treatments. The highest ETc was observed under 100% treatment; this could be due to a higher temperature and perhaps a higher radiation load from reflection of the incoming solar radiation on the crop. These results also showed that there was a general increase in soil moisture storage in the soil profile during the vegetative period (Fig. 7).

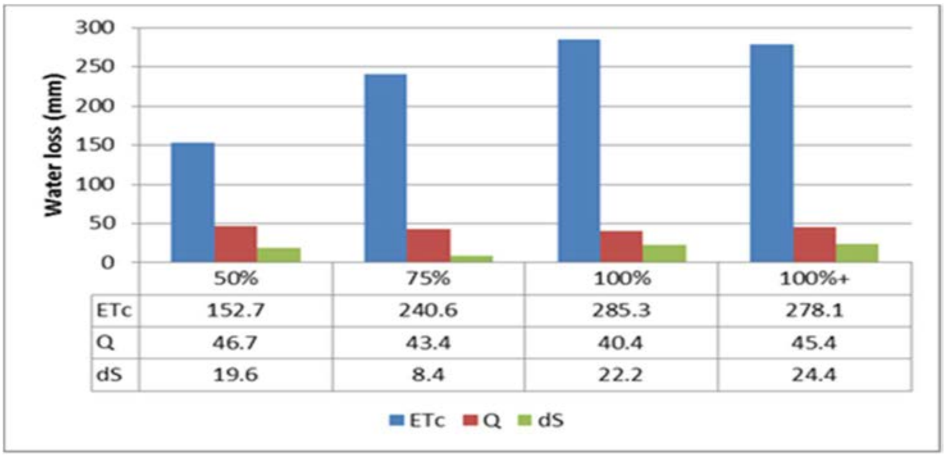

FIG. 8. Components of the root-zone water balance under the four irrigation treatments.

TABLE 5. THE ROOT-ZONE WATER BALANCE COMPONENTS DURING VEGETATIVE GROWTH

Treatment	Irrigation (mm)	Rainfall (mm)	Q (mm)	ΔS (mm)	ETc (mm)
50%	187.2	31.8	19.6	46.7	152.7
75%	260.7	31.8	8.4	43.4	240.6
100%	316.2	31.8	22.2	40.4	285.3
100%+mulch	316.2	31.8	24.4	45.4	278.1
mean			18.7	44.0	239.2
Fprob			0.24	0.98	<0.001
CV (%)			59.1	51.6	11.3

3.3. Crop green canopy cover and estimates of transpiration and evaporation

The digital pictures of vertical crop canopy were taken fortnightly during the growing season to estimate the percentage of green canopy cover during the growing season. The green canopy cover data were analyzed to estimate transpiration component of crop evapotranspiration during the growing period. The canopy cover was analyzed using the Green Crop Tracker software [18]. The results on the canopy cover analysis are presented in Figures 9 and 10, indicating that component of transpiration was negligible during the first 25 days after transplanting (DAT) and thereafter the component started increasing exponentially.

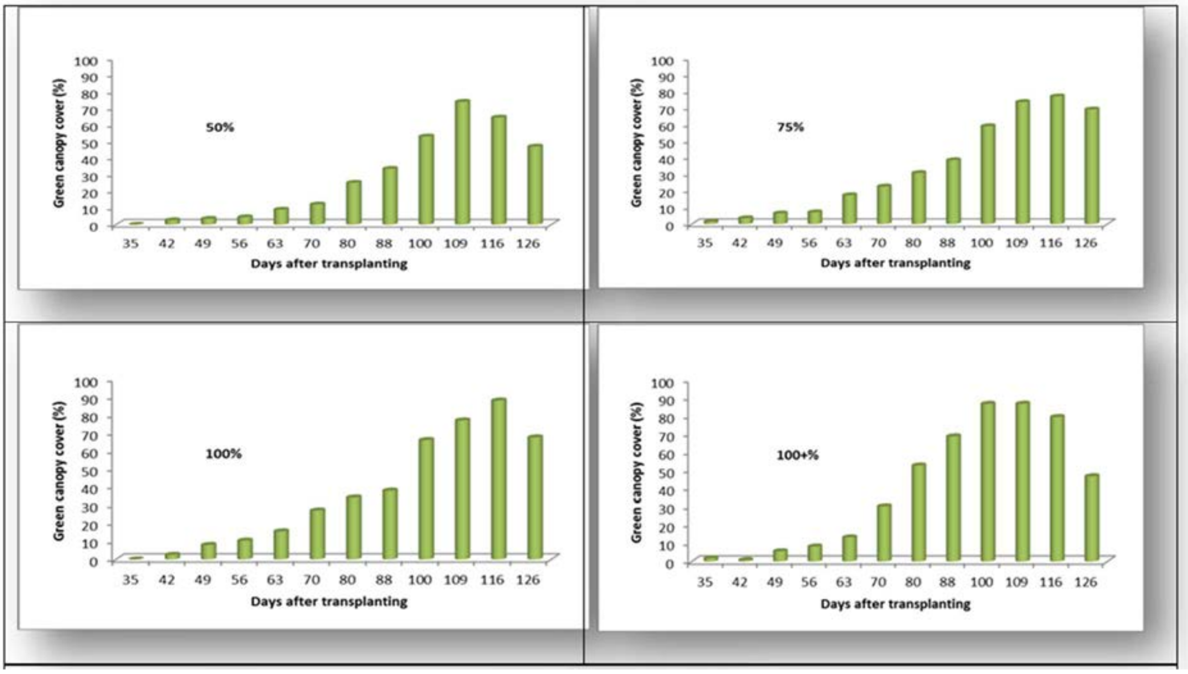

FIG. 9. Green canopy cover under four irrigation treatments.

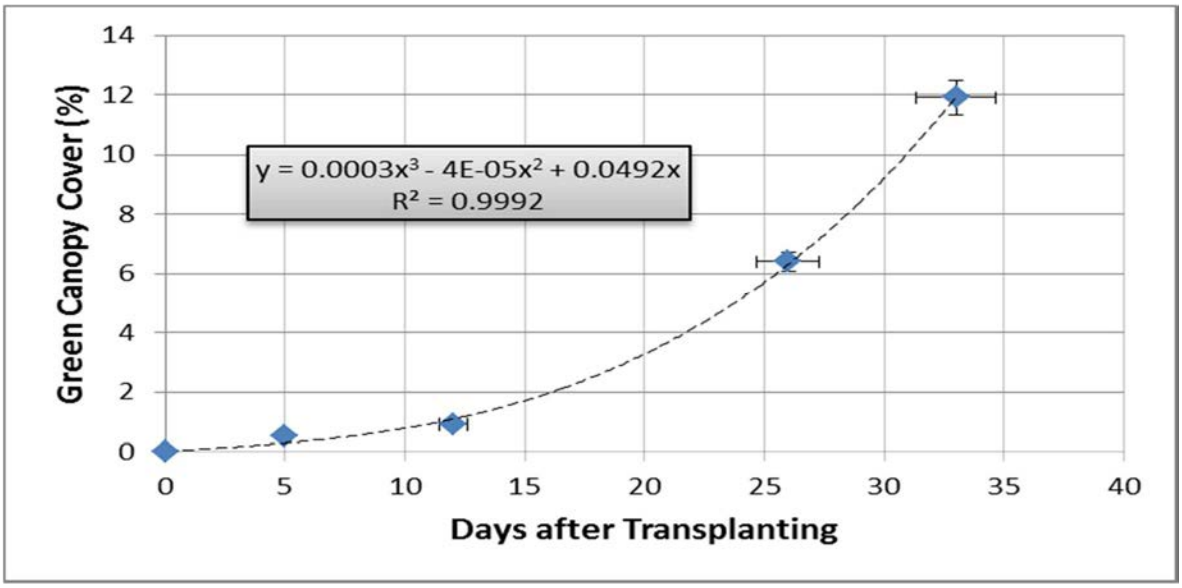

FIG. 10. Green canopy cover estimate during the vegetative period.

3.4. Partitioning of et into evaporation (e) and transpiration (t)

Table 6 and Figure 11 show the results of the partitioning of ET into E and T. The partitioning was achieved by using the canopy cover (CC) values which were then converted to L through the equation L=-1.849 ln(CC) [18]. This was subsequently multiplied with ET to give the evaporation estimates E=ET*exp(-0.61L) [15]. The water loss by transpiration was calculated by subtracting the E component from the calculated ET from the root-zone soil water balance. The transpiration (T) estimates varied from 38 mm to 70 mm, resulting in an average value of 58.8 mm. It should be noted that T for the treatment with plastic cover was 5 mm lower than those in the 100% ETc treatment and. Most of the water loss through E occurred during plant establishment before the plastic cover was installed on the treatments. The results showed that during this vegetative stage 75% of ET was E while the remaining 25% was lost through T. As presented in Fig. 8, during early stages of crop establishment, the water loss through ET was mainly in form of E but later the contribution of T started to increase.

TABLE 6. PARTITIONING OF ETc (E+T), BIOMASS PRODUCTION AND WATER PRODUCTIVITY DURING THE VEGETATIVE STAGE

Treatment (% ETc)	ETc (mm)	E (mm)	T (mm)	Biomass (kg/ha)	WP (ET) (kg/ha/mm)	WP (T) (kg/ha/mm)
50	152.7	114.1 (75%)	38.7 (25%)	232.6	1.52	6.01
75	240.6	179.3 (74%)	61.3 (26%)	310.7	1.29	5.07
100	285.3	215.0 (75%)	70.3 (25%)	421.3	1.48	5.99
Mean	226.2	169.5 (75%)	56.8 (25%)	321.5	1.43	5.69
	<0.001	<0.001	<0.001	<0.001	ns	ns

†ET = evapotranspiration, E = evaporation, T = transpiration, WP = water productivity

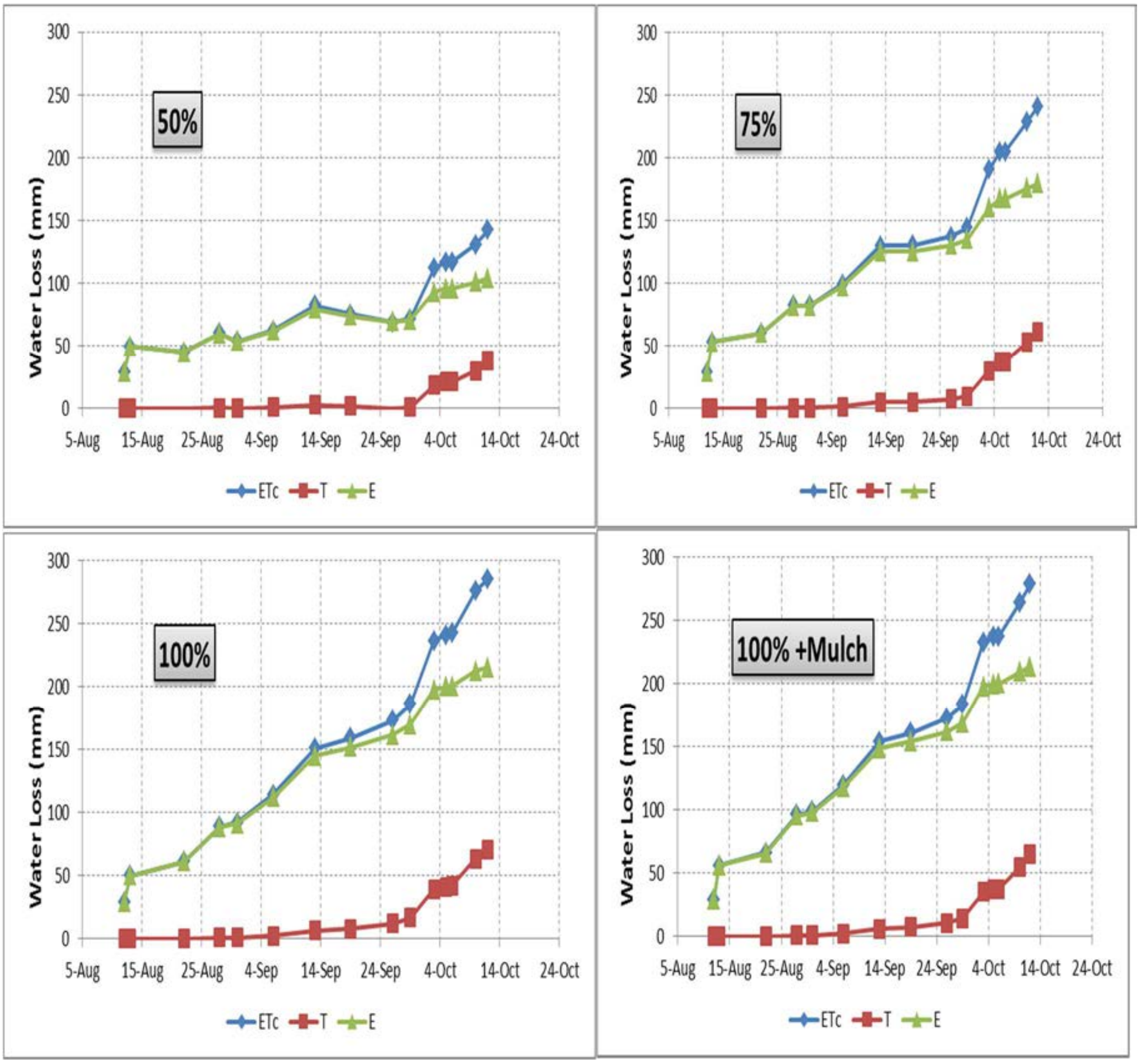

FIG. 11. Partitioning of cumulative water loss through E and T during the vegetative period.

3.4.1. Cumulative evapotranspiration

The result of the relationship between cumulative ET and applied water is presented in Fig. 12. The relationship seems linear during this period however the values were well below the 1:1 line, indicating that the applied water not only lost through ET but also through other sources and in this case most likely through deep drainage. This was expected during the early vegetative stage of growth when crop water uptake is low. The deviation from the 1:1 line seem to increase (widen) with advances in the vegetative growth indicating further losses not being accounted for.

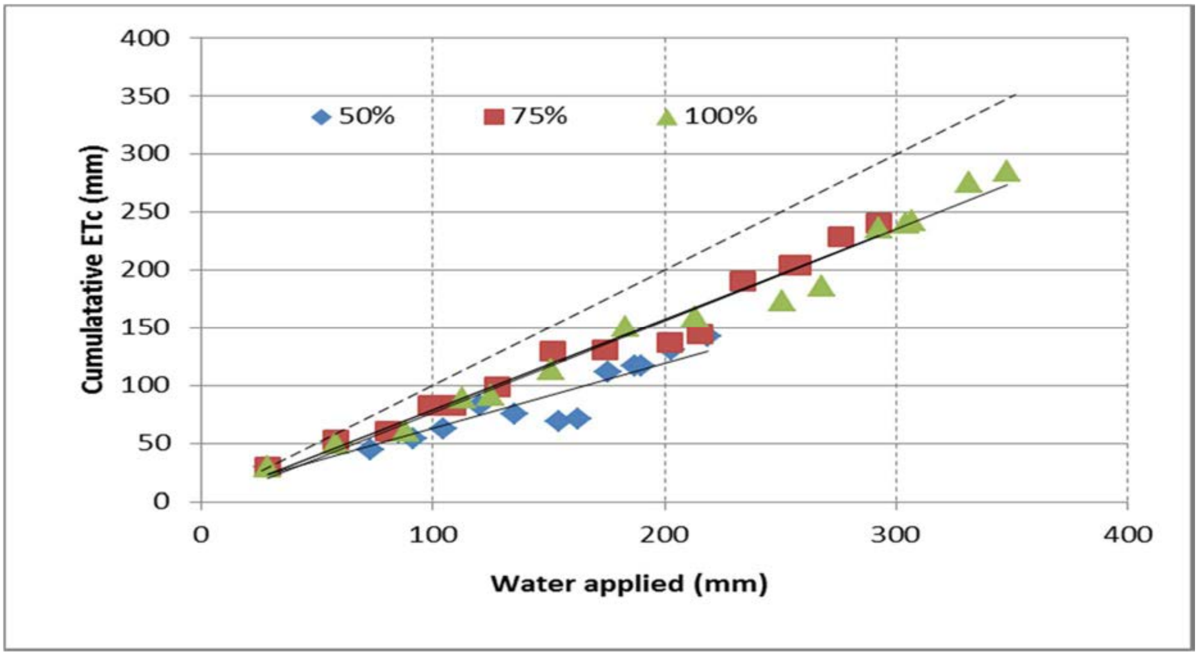

FIG. 12. Relationship between cumulative ET and applied water during the vegetative growth.

3.4.2. Cumulative transpiration

Fig. 13 presents the results on the cumulative T with the applied water during the vegetative growth. The relationship is linear with no significant differences between the 75% and 100%; however there were differences with the 50% treatment. The none significant differences in the 75% and 100% treatment may be attributed to the fact that the plants were small and the plants were not large enough to influence water loss through T. However differences were observed when compared with the 50% treatment.

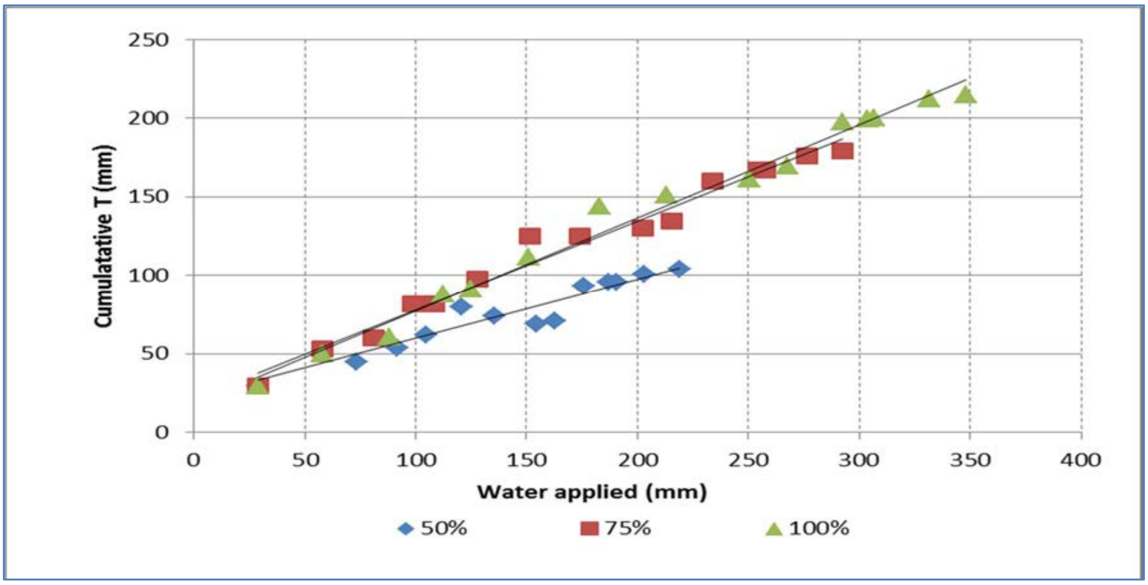

FIG.13. Relationship between cumulative T and applied water during the vegetative growth.

3.5. Biomass Productions

The results on biomass production measured during the vegetative growth are presented in Fig. 14. The results showed that the higher the amount of water applied, the higher was the amount of biomass produced. This indicated the detrimental effect of water stress to biomass production and the final yield obtained.

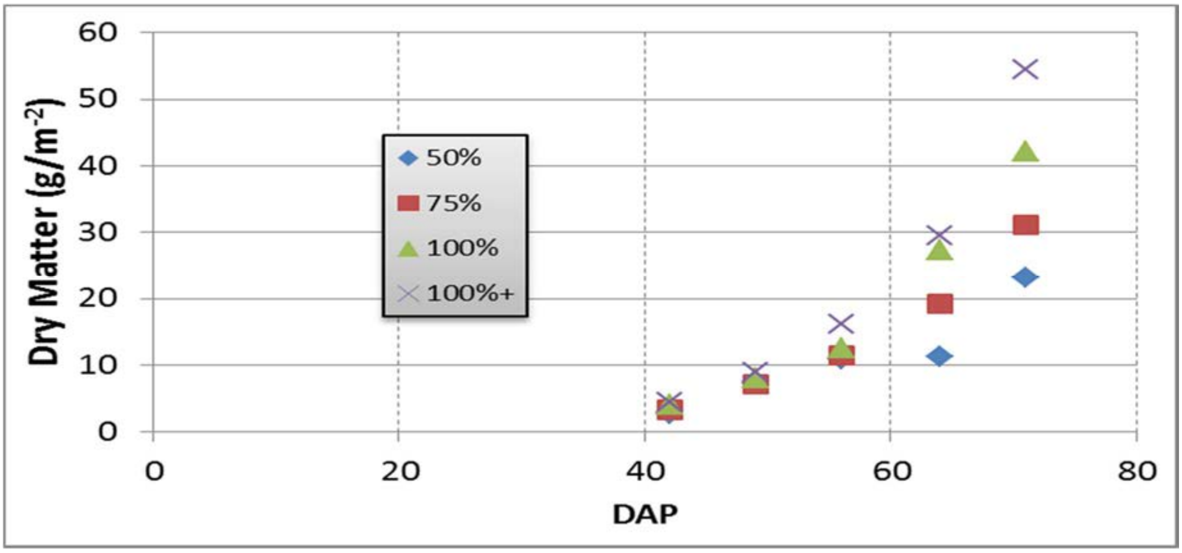

FIG. 14. Biomass production during vegetative growth.

4. CONCLUSION

The root zone water balance was computed for the vegetative period for the paprika crop. During this period the transpiration was successfully estimated from evapotranspiration data obtained from the root-zone water balance. From the moisture and hydraulic head profiles, the estimates of drainage below root-zone and change in water storage in the root-zone were made. The crop evapotranspiration was solved from the root-zone soil water balance equation and consequent estimation of transpiration using canopy cover data. The root-zone water balance computed for the vegetative period for the paprika crop led to the portioning of ET into E and T. In conclusion, the present study has shown that during the vegetative growth stage, 78% of the applied water was lost through ET. Out of the water loss through ET, 75% constituted E while the remaining 25% was T, indicating significant saving of water can be achieved through better irrigation scheduling and minimizing soil evaporation by improving management practices such as increasing planting density, improving soil fertility to enhance crop growth, mulching or application of crop residue to minimize soil evaporation.

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EVALUATION OF CARBON ($^{13}C/^{12}C$) AND OXYGEN ($^{18}O/^{16}O$) ISOTOPIC DISCRIMINATION IN WHEAT UNDER WATER STRESS CONDITIONS AND THEIR RELATION WITH CROP TEMPERATURE INDEXES

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Abstract

A study was carried out between 2008 and 2012 to evaluate the effect of water stress on wheat crop using carbon isotope discrimination ($\Delta^{13}C$) and oxygen isotopic ratio ($^{18}O/^{16}O$) and to define crop water parameters through infrared thermometry and porometry, and determine relationship between these parameters and isotopic ratios of C & O at field scale, to calculate water-use efficiency (WUE [g grain yield/m^2/mm ET]) for wheat under different water applications. Field experiments were conducted with 4 irrigation treatment (no irrigation; I_1, low: I_2, moderate: I_3 and high irrigation stress: I_4) at Saraykoy Research Station in Ankara-Mürted Basin. Additionally for 2011–2012 growing season, an irrigated treatment on a large field (5 ha) was carried out to evaluate E&T partitioning using the Keeling plot method. In all the above studies, soil moisture was measured with neutron probe. Infrared thermometer and porometer devices were used to measure canopy temperature, stomatal conductance on plant samples. Isotope compositions of carbon and oxygen were determined from soil, plant and atmospheric water vapour. At the end of the study average wheat yields were 3.35 t/ha, 4.54 t/ha, 4.22 t/ha and 4.31 t/ha, respectively for the I_1, I_2, I_3, I_4 treatments. The highest yield was obtained from the full-irrigation treatment while the lowest yield was obtained from the no-irrigation treatment. Average harvest index values were found to be respectively 29%, 31%, 32% 31% and 32%, again according to the treatments. The proportion of transpiration as percent of total ET was between 70.5 to 96% before irrigation while it was approximately 70% after irrigation. A significant positive relationship was found between carbon discrimination (Δ) and yield ratio of both grain and leaf, while a significant but negative correlation between the water-use efficiency (WUE). The positive relationship between the stomatal conductance and yield and the increase of the transpiration from the pores in environments without any irrigation restriction indicate an increase in the plant biomass and yield. This result showed that WUE is more strongly dependent on stomatal conductance. The study showed that irrigation should be recommended to be applied after heading period which increases WUE in Central Anatolia Region of Turkey. Crop water stress index is a useful tool for detecting crop water stress.

1. INTRODUCTION

Turkey in particularly the Central Anatolia region, encounters major drought due to the negative effects of the climatic change and the lack of rainfalls. The most important factor affecting the yield under arid and semi-arid conditions such as the Central Anatolia region is to use the limited water supply in the most efficient fashion. The main objective under the conditions of limited water is to obtain maximum benefit per unit water use. To achieve this: i) it is necessary to know the effective water use and to improve the crop water yield (to increase the marketable crop yield per unit water received by the crop); ii) to reduce the water loss from the root zone other than the water needed by the crop; and iii) to increase the soil water storage in the plant root zone by means of soil and water management at farm and basin levels.

Crop biomass production is associated with the total water use and water use efficiency (WUE, the net ratio of CO_2, assimilation ratio, transpiration ratio) particularly under the conditions of limited water. Although water stress is well-known, the relationship between water stress and yield is not fully evaluated in many field studies. During water stress, the stomata (pores) close to avoid evaporation. This reduction in stoma resistance helps to conserve water but also reduces the amount of CO_2 absorbed by the leaves for photosynthesis. Therefore, the increase in water use efficiency normally leads to a decrease in the amount of total dry matter.

An efficient irrigation scheduling at field level can minimize water losses by soil evaporation and maximize water uptake by crop transpiration. To achieve this, monitoring separately crop transpiration and soil evaporation, and quantifying their inter-relations is important. However, most of the scientific and technical literature concerned with crop water requirements and irrigation scheduling reported soil water consumption at field level as a whole ‘evapotranspiration’ (ET), which is the combined process of crop transpiration and soil evaporation [2].

The carbon isotopic technique has been shown to be useful for evaluating crop yield response to water stress and water use efficiency. The ratio of the abundances of carbon-13 (^{13}C) and carbon-12 (^{12}C) or carbon isotope discrimination ($\Delta^{13}C$), can play an important role in the selection of crop species in breeding studies.

Stable isotopic tracer methods have been used to separate E and T [3, 4]. This is possible because E and T fluxes often have distinct isotope ratio values in water (delta oxygen-18 [$\delta^{18}O$] and delta hydrogen-2 [$\delta^{2}H$]). Delta (δ) values are defined as the deviation of the molar ratio of heavy (rare) to light (common) isotopes in the sample relative to that of an internationally recognized standard. Hence measurements of the isotope ratio composition in the atmospheric water vapour within the canopy boundary layer or in the residual soil water over time can provide quantitative information about the sources of and processes controlling water exchange in the soil–plant–atmosphere system [3, 4]. With recent developments in laser absorption spectroscopy, real-time, in situ and continuous measurements of $\delta^{18}O$ and $\delta^{2}H$ in air vapour and liquid water are now possible [5], allowing continuous ET partitioning on a diurnal basis.

Nuclear and isotopic techniques play an important role for improving the efficiency of water use. Neutron probe is a globally approved device to measure and monitor the soil water content.

2. MATERIALS AND METHODS

2.1. Experimental site characteristics

The experimental sites are located in Ankara Murted Basin ($39^{o}57^{'}$N and $32^{o}53^{'}$E) of Central Anatolia region of Turkey (Fig. 1). A field experiment was conducted to demonstrate the effect of water stress on yield and on the agronomic characteristics of wheat under different irrigation treatments during the period October 2008 to July 2012 in Research Farm Station of Soil, Fertilizer and Water Resources Central Research Institute in Ankara, Turkey.

FIG. 1. Experimental design.

The soil of the experiment areas ranges in texture from silty clay in the top 0.30 m to clay texture for roughly 1.5 m below the surface. Field capacity on the volume basis of the top and subsoil is 33 and 37%, and wilting point, 17 and 23%, respectively.

Wheat and barley are the most important crops in region, but yields are irregular, and crops fail in years of drought. Most of the wheat is planted in late fall, as soon as there is significant moisture for seeding. Bayraktar wheat variety was used as trial crop. Wheat seeds were obtained from National Seeds Research Institute.

The climate is characterized as semi-arid in this region. In Ankara-Murted Basin temperature differences between night and day and summer and winter are sharp, and rain is relatively infrequent. Winters are long and cold with heavy snowfall while summers are short but hot. The rainiest months are November and May. Almost no effective rain falls during summer. Average annual rainfall is about 350 mm and evaporation 1 300 mm for the past 30 years.

Irrigation water was applied with surface irrigation method. Irrigation water quality was highly saline (Electrical conductivity EC 1.76 dS/m) but non-alkaline.

2.2. Crop management and experimental design

The experiment consists of four irrigation regimes with four replications, giving a total of 16 plots:

I_1 = Rainfed

I_2 = Full irrigation (irrigate to FC when calculated soil water depletion is 60 mm)
I_3 = Limited irrigation (2 irrigation maximum): one at tillering and another at grain filling to FC
I_4 = No irrigation after crop establishment until heading, after which irrigation when soil water depletion is 60 mm below field capacity.

Plot dimensions were 3.5 m x 5 m = 17.5 m^2 for seeding and 1.2 m x 4 m = 4.8 m^2 for harvesting. Experimental field was cultivated and prepared before sowing. Based on soil fertility analysis results at the start of the growing seasons in 2008–2012, commercial N fertilizers were applied (banded) about 10 cm to the side of the seed row. In general, 220 kg/ha ammonium sulfate was applied before sowing and another 350 kg/ha ammonium sulfate were applied on 15 March of each year. Sufficient phosphates were applied (175 kg/ha DAP) to ensure adequate P nutrition. Winter wheat was planted around 20 October of each year.

Precipitation, air temperature (maximum, minimum and average), class A pan evaporation, wind speed, relative humidity, global radiation and sunshine hours were obtained on hourly basis from meteorological station (50 m away from experimental site).

One Soil Moisture Neutron Probe aluminum access tube was inserted to 100 cm depth in each plot. During access tube installation care were exercised to minimize gap and soil disturbance. Soil samples were taken from each plot for chemical and physical analysis.

Soil moistures content in the plots was monitored using a neutron probe (CPN) with aluminum access tubes. The measurements were taken at 0–20, 20–40, 40–60 and 60–90 cm soil depth. The neutron probe observation was made two times a week in all access tubes. The neutron probe was calibrated at the beginning of the growing season in 2008 with the following calibration equation $\theta_V = 18.195\ CR + 8.2138$, $R^2=0.963^{**}$ (θ_V: volumetric soil water content, CR: count ratio). Calibrations were repeated every year before plot installation.

The amount of soil water in the 0–90 cm depth was used to initiate irrigation. These data were also used to calculate crop evapotranspiration (ETc). ETc was calculated as the soil water balance residual for the time periods between two successive soil water content measurement dates. Prior to wheat planting, all plots were precision leveled to zero-grade and runoff was eliminated by earthen embankments around the wheat plots.

Decagon SC-1 Leaf Porometer was used to measure stomatal resistance of leaf. Porometer measures stomatal aperture in terms of leaf conductance to water vapour. This is a major determinant of water loss from wheat leaves and of CO_2 uptake during photosynthesis.

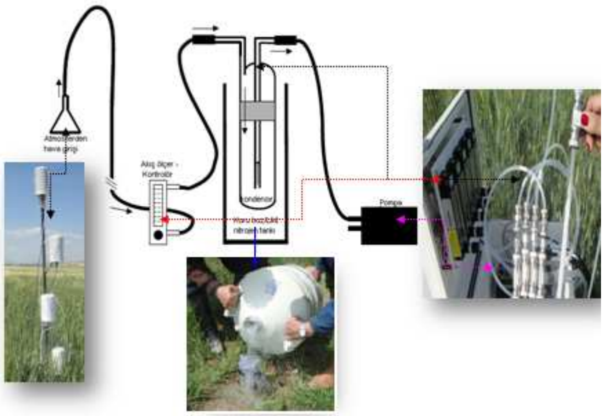
The crop water stress was monitored using Fluke 66 Model infrared thermometer. The crop canopy temperature measurements were taken at least 12 replications over each irrigation treatment. Measurements were taken between 13:00 and

14:00 h on cloudless days. Canopy temperatures were used to determine Crop Water Stress Index (CWSI).

Photos taken with camera were used to calculate canopy cover. Overhead photographs of the canopy were taken with commercial digital camera and the photographs were processed with the GreenCrop Tracker software which was freely distributed software from ITT: http://www.ittvis.com.

For carbon isotope discrimination study, 10–20 south-facing sun-lit leaves of five marked plants per treatment were collected once at the stage of pre-anthesis. Only fully mature leaves from the latest growth period were used. Leaves were oven dried at 60°C for 48 h and milled to fine powder for carbon and oxygen isotopic analysis. The isotopic composition of C and O were determined using standard mass spectrometric techniques (at the IAEA, Seibersdorf Stable Isotope Laboratory in Vienna, Austria).

For measurement associated with oxygen-18, plant stem tissue samples were also taken at the bottom of the plant near soil surface. Approximately 2–3 grams of fresh stem tissue were placed in a screw-cap glass vial and the top of the cap covered with parafilm. Soil samples were taken from 0–5 cm and 5–10 cm soil depths.



Cryogenic traps were installed to collect atmospheric vapour samples in two big plots. Air vapour was collected on 5 May 2012 before irrigation, and 26 May after irrigation. Measurements were performed at five sampling heights which was at the soil surface (0–5 cm), near the bottom of the crop canopy (20 cm), near the middle of the crop canopy (50 cm), at the top of the crop canopy (1 m) and at 1 m height above the top of the crop canopy (2 m) heights through the vegetation profile. Air humidity and temperature were measured at each sample height. The vapour samples were collected in small glass vials and were sent to IAEA laboratory to be analyzed for isotopic composition.

Irrigation water and soil chemical and physical properties such as pH, EC, field capacity (FC), wilting point (WP), bulk density, infiltration, texture were analyzed. Wheat was harvested on 20 July almost every year. After harvest, grain yield, straw and biomass were measured.

3. RESULTS AND DISCUSSION

The experiments were carried out over four winter wheat growing seasons between 2008 and 2012. The first year (2008–2009) of experiment wheat soilbore mosaic virus symptoms were noticed at the beginning of May on all experimental plots. The fungus invaded root hairs of the young wheat crop in the spring period of high soil moisture, resulting in an estimated 10 to 20% yield loss. As a result, yield for the 2008–2009 cropping season was not reported. The experimental plots were repeated in the disease-free areas and seeds were analyzed before sowing in the following years.

3.1. Climatic data

Daily rainfall and ET_0 between 2008 and 2012 was given in Fig. 2. As apparent from the graph, although the amount of rainfall during the winter months in 2010–2011 was not high, it was high in autumn and spring periods. The amount and distribution of the rainfall in the spring caused a reduction in the number and amount of the irrigation on the plots that were subjected to water treatment. This situation was the same for the 2011–2012 growing period.

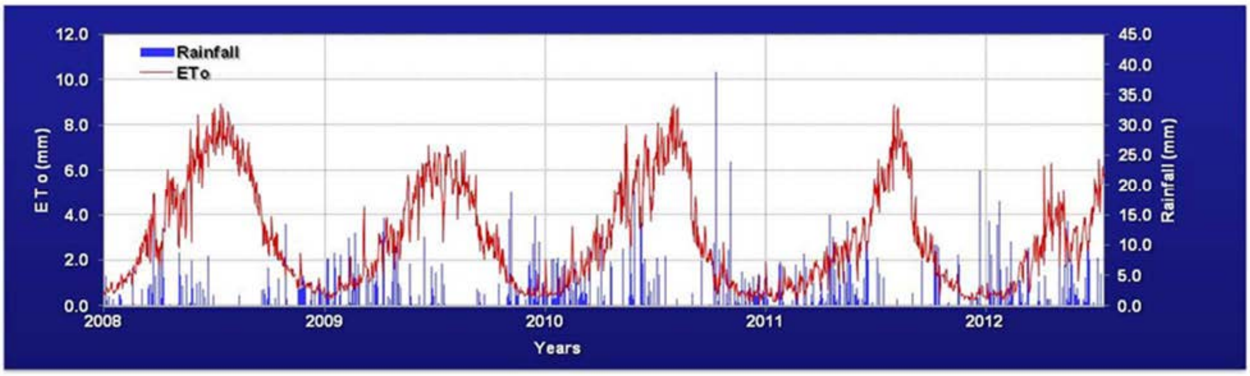


FIG. 2. Daily rainfall and ETo distribution between the years of 2008–2012.

3.2. Irrigation

According to the treatments, irrigation was applied taking into consideration measured soil moisture content. For the full-irrigation treatment, the initial soil moisture content value was at field capacity. In the subsequent irrigations, when the soil water content was 60 mm lower than the field capacity value, it was re-irrigated to field capacity. During the trial, the soil moisture content did not drop to the level requiring irrigation until end of April for 2009–2010 and 2010–2011 growing season and until June for 2011–2012 growing season, due to the high amount of the fall and winter rainfall. The irrigation dates and water amounts applied according to the treatmens is given in Table 1.

TABLE 1. IRRIGATION AMOUNTS AND THE DATES OF APPLICATION

Irrigation water amount (mm)														
2009–2010					2010–2011					2011–2012				
Date	I_1	I_2	I_3	I_4	Date	I_1	I_2	I_3	I_4	Date	I_1	I_2	I_3	I_4
28.10.09	-	90	-	-	25.10.10	-	85	-	-	19.06.11	-	60*	60	60
29.04.10	-	60	60	-	25.04.11	-	-	56	-					
20.05.10	-	60	-	102	12.05.11	-	60	-	60					
15.06.10	-	60	111	60	14.06.11	-	60	60	60					
TOTAL	0	270	171	162	TOTAL	0	205	116	120	TOTAL	0	60	60	60

*Soil moisture did not reach soil water depletion of 60 mm until 19 June.

According to the trial plots, the total irrigation water applied in the I_2, I_3 and I_4 treatments was 270.0, 171.0 and 162.0 mm, 205.0, 116.0 and 120.0 mm and 60 mm, 60 mm and 60 mm, respectively during the growth period of 2009–2010, 2010–2011 and 2011–2012.

3.3. Soil water content

Soil water measurements were made twice a week after the wheat sowing. The measurements were not started until the beginning of April due to the wet winter conditions and the snow covered in January, February and March of each year. At the beginning of April, the soil water content reached to the same level in almost all the treatments after the snow cover melted away. The measured values of the soil moisture content, the amount of rainfall and irrigation water applied according to the treatments are provided in the same graph. The growth graphs plotted separately for the periods of 2009–2010 and 2010–2011, from April to the harvest, are given in Fig. 3 and 2011–2012 whole period and spring period were given in Fig. 4.

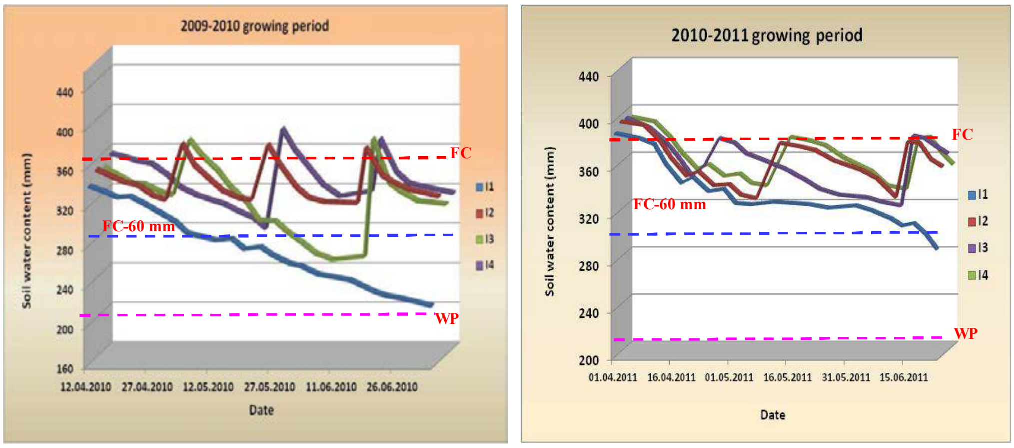


FIG. 3. Soil water content data (for the growth period of 2009–2010 and 2010–2011).

The soil moisture content declined to the values of wilting point in the periods towards the harvest in the plot (I_1) to which no irrigation was applied during the growth period of 2009–2010. When the value of soil moisture felt 60 mm below the FC value in the plots of full irrigation (I_2) and irrigation after the period of heading (I_4), the deficit moisture was completed to the FC via irrigation. The moisture present in the soil was brought up to the FC value in the plot (I_3) to be irrigated for once at the tillering and grain filling for once. Changes in the soil moisture showed a compatible change depending on the rainfall and irrigation treatments.

As apparent from Fig. 3, the soil moisture content remained above the values of wilting point even in the plot (I_1) to which no irrigation was applied for the growth period of 2010–2011 due to the rainfalls. The soil moisture content was brought up to the field capacity in the full irrigation plot (I_2) after planting and the deficit moisture was completed to the FC when the soil moisture value felt 60 mm below the FC value in the subsequent irrigations.

After the period of heading, the first irrigation in the (I_4) plot was applied in May while the second irrigation in June. The moisture present in the soil was brought up to FC value in the plot (I_3) to be irrigated at tillering stage for once and at the grain filling for once for the purposes of the irrigation treatments although the moisture value present in the soil did not fall more than 60 mm below the FC in April.

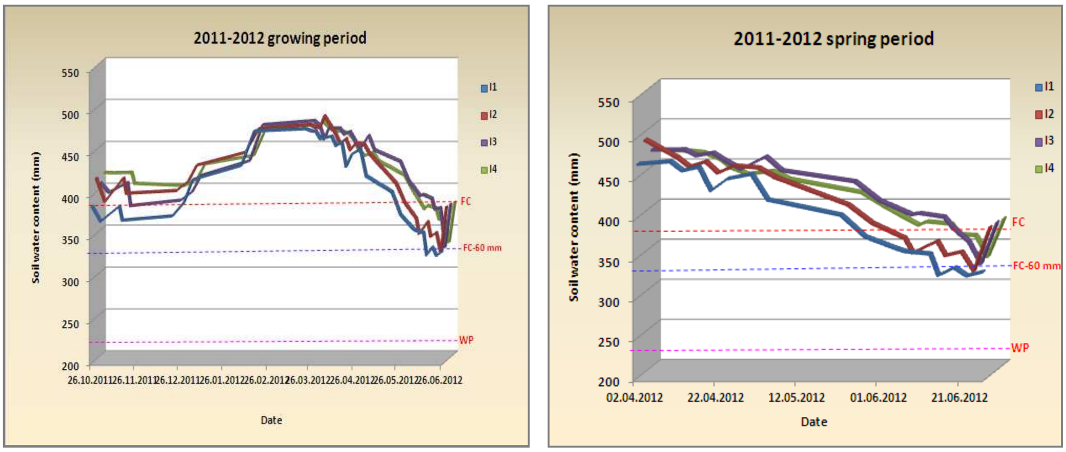


FIG.4. Soil water content data (for the growth period of 2011–2012).

It can be seen in Fig. 4 that soil water content was very high for the growing season of 2011–2012. Soil moisture was higher than field capacity until the beginning of June. Soil moisture content in the irrigation plots (I_2, I_3, I_4) did not fall to the level requiring irrigation until 14 June 2012. Because of that it was not expected to find any differences between irrigation treatments.

3.4. Plant water consumption

ET value was calculated according to the ‘Soil Water Budget’ equation.

$$ET = I + P + \Delta S - R - D \quad (1)$$

I = Irrigation water (mm),
P = Precipitation (mm),
ΔS = Change in soil water content (mm),
R = Surface flow (mm),
D = Percolation from the root zone to depth.

Monthly and seasonal plant water consumptions are given in Table 2 in line with the applied irrigation water and rainfalls.

TABLE 2. MONTHLY AND SEASONAL WATER CONSUMPTION BY PLOTS

Years	Treatments	ET (mm)							
		Oct.*	Nov.	Dec.	Apr.	May	Jun.	Jul.**	Total
2009–2010	I_1	33.39	61.78	112.44	60.61	58.01	70.27	25.84	422.34
	I_2	49.47	77.96	112.43	125.67	120.14	95.29	27.89	608.85
	I_3	37.48	49.88	110.55	122.64	119.75	112.35	21.98	574.63
	I_4	33.31	57.82	106.37	68.60	92.25	107.23	20.71	486.29
2010–2011	I_1	17.53	58.33	59.31	72.50	68.16	76.92	56.23	408.98
	I_2	25.27	63.82	82.65	101.48	129.42	96.25	54.71	553.60
	I_3	14.42	50.40	57.39	105.21	99.39	105.27	57.48	489.56
	I_4	15.14	53.21	52.47	86.14	103.81	93.53	56.34	460.64

*, ** For 10 and 20 days

Soil water changes in the soil of 0–90 cm depth were used for the plant water consumption calculations. The highest water consumption occurred in the full irrigation treatments.

3.5. Yield

The highest yield was obtained from the full-irrigation (I_2) treatment. Yield values of rainfed (I_1) treatment was 23%, 15% and 19% less than irrigated (I_2, I_3, I_4) treatments respectively. Harvest index values of the plots were calculated using the average yield and biomass values (HI = grain yield / Biomass yield) in the respective treatments. The highest harvest index was found in the plot I_4, with value of 32.8 percent in the first year (Table 3).

TABLE 3. AVERAGE YIELD, BIOMASS AND HARVEST INDEX VALUES BY PLOTS

Years	Treatments	Grain yields (t/ha)	Biomass (t/ha)	HI
2009–2010	I_1	3.54	11.61	30.5
	I_2	4.58	14.90	30.7
	I_3	4.15	13.25	31.3
	I_4	4.36	13.28	32.8
2010–2011	I_1	3.16	11.54	27.4
	I_2	4.49	14.52	30.9
	I_3	4.28	13.68	31.3
	I_4	4.25	13.70	31.0

The variance analysis applied on the yield values showed no statistically significant difference at the level of 0.05 among the plots in both years [6]. Variance analysis is provided in Table 4.

TABLE 4. WHEAT YIELD VARIANCE ANALYSIS VALUES

Years	Variation Source	D.F	S.S	M.S	F	Table F	
						0.05	0.01
2009–2010	Blocks	3	0.97	0.32	0.63	3.86	6.99
	Treatments	3	2.42	0.81	4.71*	3.86	6.99
	Error	9	4.62	0.51			
	General	15	8.01				
2010–2011	Blocks	3	0.96	0.32	1.49	3.86	6.99
	Treatments	3	4.34	1.45	20.15**	3.86	6.99
	Error	9	1.94	0.22			
	General	15	7.24				

*, ** Statistically significant at P<0.05, P<0.01 respectively

In the Duncan test, two different groups emerged for the years 2009–2010 and 2010–2011. No class difference was found between the treatments I_2, I_3 and I_4 they all belonged in the first group. The no-irrigation treatment I_1 constituted the second group. The classification concerning the Duncan Test results were given in Fig. 5. The reason why there is no group difference between the irrigation treatments is that spring and winter precipitation was high in both years.

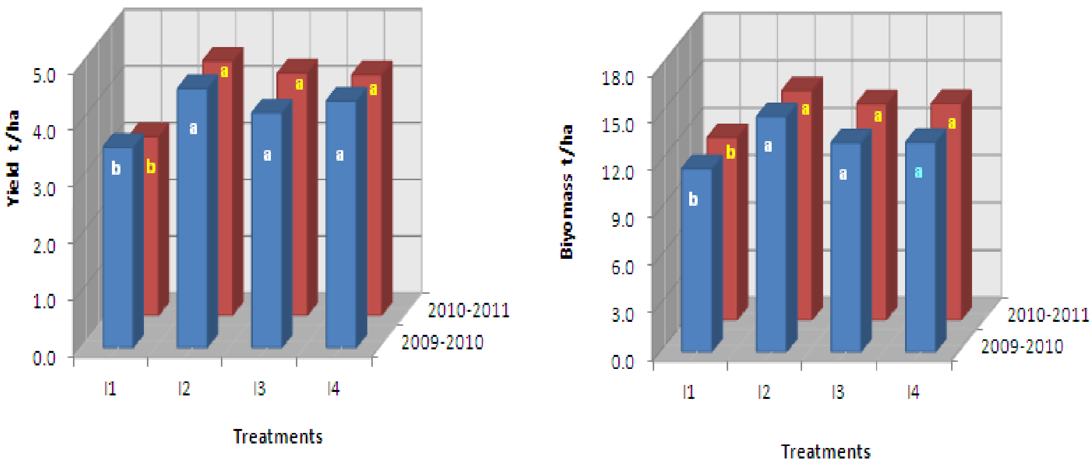


FIG. 5. Duncan classes of average biomass & yields for the treatments.

3.6. Water use efficiency (wue)

WUE values calculated according to the years when the trial was carried out are given in Table 5. The WUE values obtained are in line with global wheat WUE which ranges from 4.0 to 18.3 kg/ha/mm on the yield basis.

TABLE 5. WUE VALUES BY PLOTS

Years	Treatments	ET (mm)	Yields (t/ha)	Irrigation (mm)	WUE (kg/m^3)
2009–2010	I_1	422	3.54	-	8.38^b
	I_2	609	4.58	290	7.52^b
	I_3	575	4.15	183	7.22^b
	I_4	486	4.36	162	8.97^a
2010–2011	I_1	409	3.16	-	7.72^b
	I_2	554	4.49	205	8.10^b
	I_3	490	4.28	120	8.73^b
	I_4	461	4.25	104	9.22^a

As for the WUE in 2009–2010, the best outcome was provided by the I_4 (irrigation when the soil water potential diminished 60 mm beginning from the period of heading stage). It was followed by I_1 (no-irrigation) and I_2 (full irrigation). The water use had the lowest efficiency in the I_3 treatment (irrigation in which the moisture present in the soil was brought up to field capacity once at the tillering stage and at grain filling stage). For the growth period of 2010–2011, WUE in I_4 treatment has a value of 9.2 kg/m^3 and it was followed by I_3, I_2 and I_1 with the values of 8.7, 8.1 and 7.7 kg/m^3, respectively. The more effective water-use in winter wheat crop was obtained with treatment I_4 (no irrigation until heading, after will irrigate calculated soil water depletion is 60 mm).

3.7. Stomatal conductance

At the beginning of the study, the evaluation of results was made as the conductance instead of resistance since the porometer calibration was performed as the measurement of stomatal conductance instead of the measurement of stomatal resistance. The porometer readings were made twice a week in April, May and June (from the date when plant leaves reached the level to be read, to the date when the plant leaves started to dry) as from the date when the irrigation was initiated. No reading was made in the rainy or very windy days since accurate results would not be obtained under those conditions. The readings are provided in Table 6.

TABLE 6. STOMATAL CONDUCTANCE VALUES

Date	I_1	I_2	I_3	I_4
19.04.2010	258	263	241	252
22.04.2010	189	215	170	195
26.04.2010	152	158	157	164
30.04.2010	162	275	286	160
03.05.2010	155	215	229	127
06.05.2010	122	165	181	119
13.05.2010	104	118	126	107
20.05.2010	102	205	112	198
27.05.2010	105	134	105	132
03.06.2010	101	144	108	126

As seen in Table 6, the stomatal conductance decreased in the no-irrigation treatment. It can be deduced from this data that the pores were closed under rainfed, water-stressed conditions. The highest stomatal conductance was obtained from the full irrigation treatment, especially in the observations made after irrigation applications. The stomatal conductance results plotted according to the treatments is given in Fig. 6.

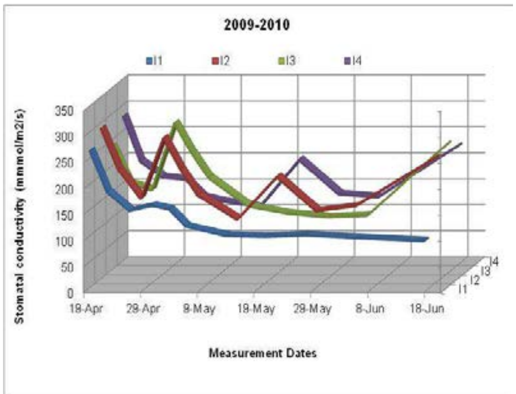


FIG. 6. Stomatal conductance by treatments (for the growth periods of 2009–2010).

The porometer readings were made in the same way in April, May and June for the growth period of 2010–2011. Porometer readings could not be made as often as desired due to the frequent rainfalls occurred every other day in April. The readings made are provided in Table 7.

TABLE 7. STOMATAL CONDUCTANCE VALUES

Date	I_1	I_2	I_3	I_4
11.04.2011	261	265	250	256
26.04.2011	178	181	271	170
03.05.2011	154	162	216	156
06.05.2011	143	148	181	141
12.05.2011	121	200	166	178
26.05.2011	116	173	150	154
02.06.2011	110	155	133	133
08.06.2011	107	131	121	126
11.06.2011	103	119	115	112
16.06.2011	103	206	212	210

Stomatal conductance was measured lower in the rainfed treatment (I_1) compared to the other treatments. An increase in the stomatal conductance was observed after each irrigation event. In the full irrigation, the difference that occurred in the last year was less than in this year compared to the other irrigation treatments. It is considered that the efficiency of full-irrigation treatment was less due to the continuity and distribution of the spring rainfall in the year 2011. The graph plotted for the results of the stomatal conductance according to the treatments is given in Fig. 7.

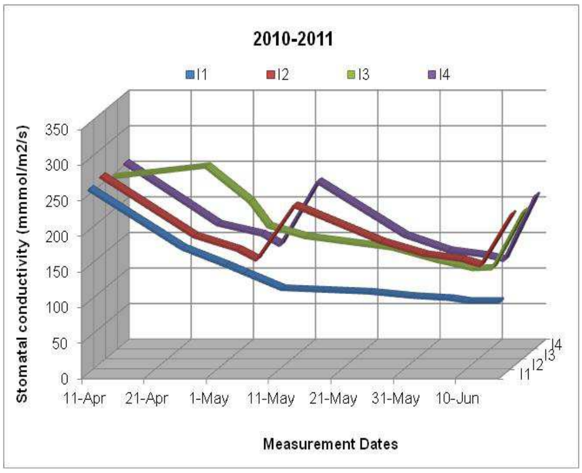


FIG. 7. Stomatal conductance by treatments (for the growth periods 2010–2011).

3.8. Crop water stress index (cwsi)

Crop water deficit was monitored using CWSI. This index was computed using the method suggested by [7].

$$CWSI = \frac{(Tc - Ta) - (Tc - Ta)_{LL}}{(Tc - Ta)_{UL} - (Tc - Ta)_{LL}} \tag{2}$$

where:

T_c (°C) is the canopy temperature;
T_a (°C) the air temperature;
$(T_c\text{-}T_a)_{LL}$ is lower limit of canopy-air temperature difference;
$(T_c\text{-}T_a)_{UL}$ is upper limit of canopy-air temperature difference.
The differences $(T_c\text{-}T_a)_{LL}$ was obtained from the linear regression for the crop under no water stress and $(T_c\text{-}T_a)_{UL}$ when the crop is under maximum water stress condition.

The non-stressed baseline, $(T_c\text{-}T_a)$ versus vapour pressure deficit (VPD) (lower limit) relationship (Fig. 8) was determined using data collected in full irrigation treatment (I_2). On the other hand, the fully stressed baseline (upper limit) was computed according to the method provided by [7].

TABLE 8. CROP WATER STRESS INDEX (CSWI) VALUES

Years	Treatments	CSWI
2009–2010	I_1	0.93
	I_2	0.24
	I_3	0.54
	I_4	0.62
2010–2011	I_1	0.94
	I_2	0.42
	I_3	0.18
	I_4	0.29

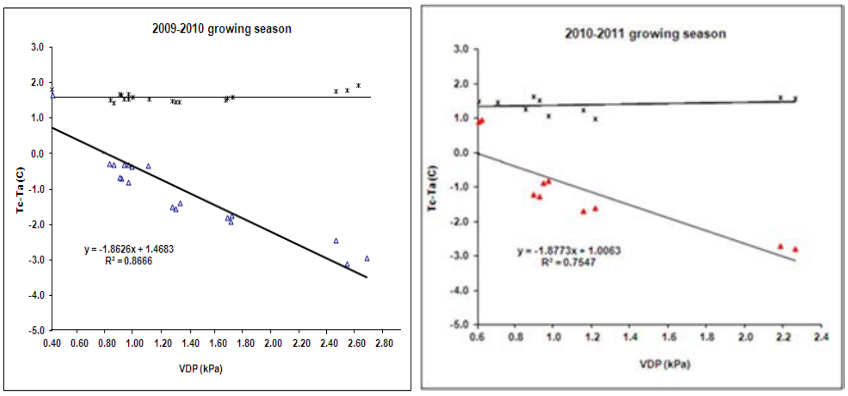


FIG. 8. T_c-T_a versus VPD relationship.

Variation of CWSI as a function of day after sowing for each irrigation treatment (I_1, I_2, I_3, I_4) during experimental period were given in Table 8 and presented in Fig. 9.

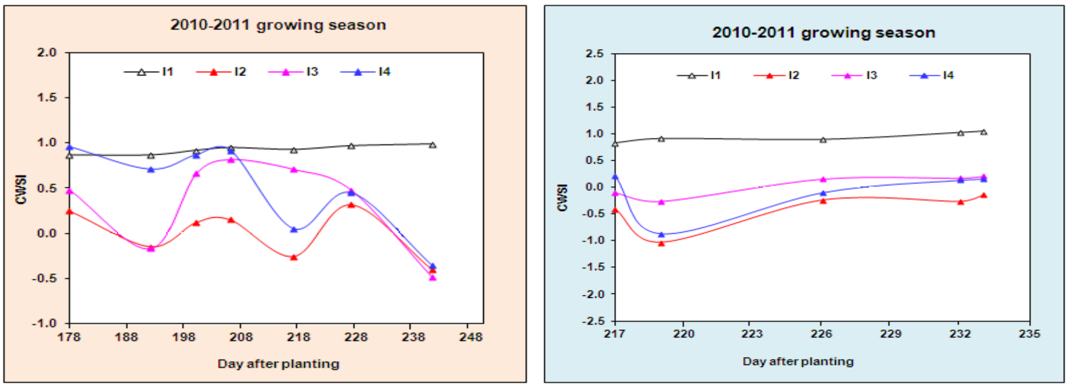


FIG. 9. Variation of CWSI as a function day after sowing for each irrigation treatment.

The CWSI values of I_2, I_3, and I_4 decreased depending on the amount of irrigation water applied. Higher values of CWSI were obtained in I_1 treatment as compared to the other treatments. This can be explained by the fact that water stress occurred as a result of less amount of water applied in soil profile.

3.9. Evaluation of the results of isotope analysis

3.9.1. Partition of Transpiration (δT), Evaporation (δE) from Evapotranspiration (δET)

Plant water consumption (ET) is an important factor in determining the water use efficiency of the land and can be determined from measurement of photosynthesis [8]. However, such measurements include instantaneous measurements only at the level of leaf. To separate the plant water consumption (ET) into the transpiration from plant (T) and the evaporation from the soil surface (E) on the crop and land basis is often difficult [4][9] [10]. In some greenhouse trials, although the evaporation from the soil surface could be avoided by covering over the pots, the evaporation from the soil was inevitable because it was difficult to make the same at the land level [11] [12]. The water evaporated from the soil surface was divided into many parts and the isotopic composition of water is quite different from the isotopic composition of the leaf water [13]. Therefore, the isotope mass balance model can be used to separate the elements present in evapotranspiration [14].

$$ET = T + E \tag{3}$$

$$ET\delta_{ET}{}^{18}O = T\delta_{T}{}^{18}O + E\delta_{E}{}^{18}O \tag{4}$$

Here, ET refers to the total plant water consumption, T wheat water consumption and E evaporation from the soil. $ET\delta_{ET}{}^{18}O$, $T\delta_{T}{}^{18}O$ and $E\delta_{E}{}^{18}O$ are respectively evapotranspiration, transpiration and oxygen isotopic composition of evaporation water.

Keeling plot method is one of the most used methods utilized to determine the partial share of E and T from ET. In the method, the evaporation from the soil (δ_E), transpiration from the plant (δ_T), and $\delta^{18}O$ isotopic composition of the total ET (δ_{ET}) are replaced into the following formula and the percentage contribution of the evaporation and transpiration to the total ET is calculated:

$$F_T\,\% = \frac{[(\delta_{ET} - \delta_E)]}{[(\delta_T - \delta_E)]} x\,100 \tag{5}$$

and

$$F_E\% = 100 - F_T\% \tag{6}$$

Here $F_T\%$ refers to transpiration percentage and $F_E\%$ evaporation percentage.

3.9.1.1. Isotopic composition of the evaporation from soil (δs)

$\delta^{18}O$ value of the soil evaporation is determined by taking into account the soil surface temperature, soil surface moisture and isotopic composition of the soil at evaporation level. In the treatments on the 0–5 cm soil surface, the sampling was made after the irrigation. The soil temperature was measured in the study when the water vapour sampling was made. Soil sampling was taken near the point where plant and atmospheric vapour sample was taken and the soil samples into glass bottles before sending off for analysis. Oxygen and deuterium contents of soil samples are given in the Table 9.

TABLE 9. OXYGEN AND DEUTERIUM CONTENTS OF SOIL SAMPLES

Date	Depth, cm	$\delta^{18}O$ (‰)	δD (‰)
05 May 2012	0–5 cm	–1.76	–52.84
	5–10 cm	–9.81	–80.84
	0–5 cm	0.26	–34.58
	5–10 cm	–4.06	–58.86
26 May 2012	0–5 cm	–6.88	–58.71
	5–10 cm	–7.02	–60.73
	0–5 cm	–6.92	–58.70
	5–10 cm	–5.37	–53.40
	0–5 cm	–6.98	–59.35
	5–10 cm	–6.40	–56.04

3.9.1.2. Isotopic composition of the transpiration from plant (δ_T)

If it is assumed that isotopic exchange is under a stable condition during the transpiration, then the $\delta^{18}O$ value of transpiration should be approximately equal to the plant water supply and can be estimated by measuring the $\delta^{18}O$ value of the water extracted from the plant stem. Samples taken from plant stem were used to determine the isotopic ratio of the water transpired. $\delta^{18}O$ and δD content present in the stem sample taken near soil surface and water content ratio contained in the plant stems are given in Table 10.

TABLE 10. THE PLANT STEM $\delta^{18}O$ AND δD COMPOSITION

Date	$\delta^{18}O$ (‰)	δD (‰)
05 May 2012	–8.66	–62.63
	–5.20	–54.08
	–6.93	–60.29
26 May 2012	–8.77	–67.82
	–6.09	–56.36
	–8.56	–65.58

3.9.1.3. Determination of the isotope composition of atmospheric water vapour (δ_{ET})

Oxygen-18 and deuterium isotopes mixing relationships (‘Keeling plots’) were generated for two sampling days on 5 May 2012 (before irrigation) and 26 May 2012 (after irrigation) taken from 10:00–16:00 in both days.

The isotopic contents of the vapour sample which were taken from different heights of the vegetation profile were analyzed by IRMS in Seibersdorf. The $\delta^{18}O$ contents of air vapour samples were presented in Table 11. The graph plotted using these values are given in Fig. 10. The slope of the graph gives the value of δ_{ET}. Lines were represented best-fit regressions.

According to Keeling plot method, it is estimated that the δD value of evapotranspiration (δ_{ET}) from Table 11 and the isotope values of plant transpiration (δ_T) and soil evaporation (δ_E) sources for each sampling day. The transpiration and evaporation (%F_E)

ratios determined using the $\delta^{18}O$ contents in the soil (δ_E) and plant stem (δ_T) were given in Table 12.

TABLE 11. ATMOSPHERIC WATER VAPOUR $\delta^{18}O$

Date	Height, cm	$\delta^{18}O$ (‰)	δD (‰)
05 May 2012	5	-13.57	-95.49
	20	-13.52	-94.94
	50	-13.34	-93.49
	100	-13.97	-97.01
	200	-13.76	-97.50
26 May 2012	5	-19.95	-137.39
	20	-19.18	-135.58
	50	-19.04	-133.89
	100	-18.44	-129.93
	200	-18.49	-130.26

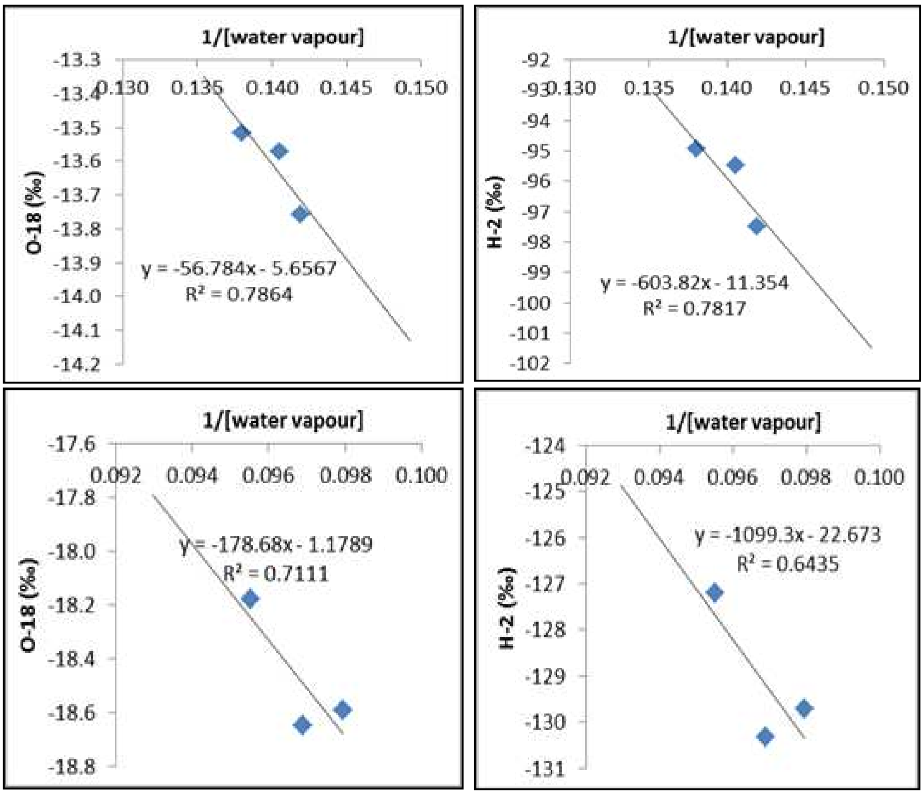


FIG. 10. The relationship between the atmospheric water vapour $\delta^{18}O$ and water content.

TABLE 12. EVAPORATION AND TRANSPIRATION PERCENT OF WHEAT

Date	T°C	RH%	$\delta^{18}Os$	δDs	$\delta^{18}Oa$	δDa
5 May 2012	20.3	30.3	–6.93	–69.8	–13.6	–95.5
26 May 2012	21.1	41.9	–6.27	–56.7	–19.9	–137.4

Date	$\delta^{18}O_E$	δD_E	$\delta^{18}O_{ET}$	δD_{ET}	$\delta^{18}O_T$	δD_T	$^{18}O\ F_T$ (%)	$D\ F_T$ (%)
5 May 2012	–36.0	–173.1	–5.7	–11.4	–6.9	–59.0	95.8	70.5
26 May 2012	–31.1	–134.3	–1.2	–22.7	–7.8	–63.3	77.8	63.6

The proportion of transpiration as percent of total ET was 70.5% on 5 May (before irrigation) while it was approximately 64% on 26 May (after irrigation).

3.9.1.4. Changes in the hydrogen and oxygen isotope ratios in the soil profile

The distribution of oxygen, and deuterium isotopes in the soil profile by treatments are given in Fig. 11. While the oxygen and deuterium ratios in the treatments with irrigation restriction (I_1 and I_4) showed a reduction in the upper layer, with a sharp evaporation front; such evaporation front was not obvious in the treatments with sufficient irrigation.

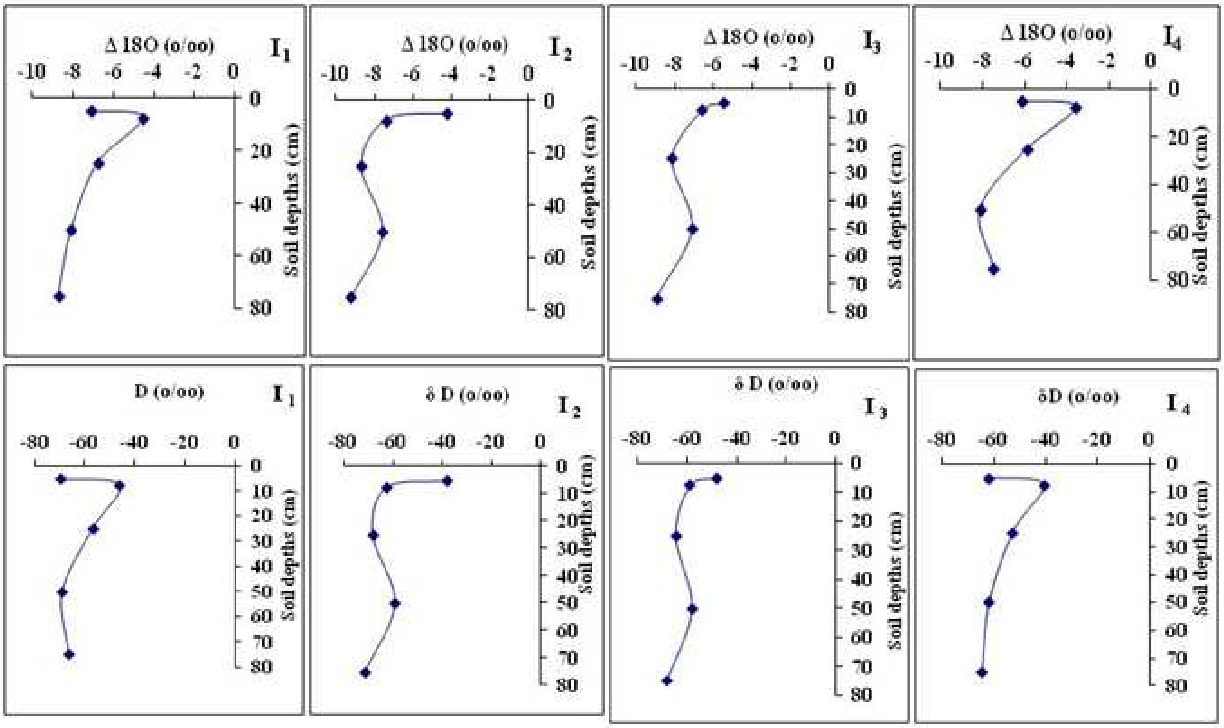


FIG. 11. Changes in the hydrogen and oxygen isotope ratios in the soil profile.

3.9.2. Evaluation of the carbon isotope ratios (Δ)

Carbon isotope discrimination (Δ) for pre-anthesis (pre-emergence, the second week of May) was applied on the leaf samples and post-harvest grain. Carbon isotope ratio ($^{13}C/^{12}C$) of the samples ($^{13}C/^{12}C_{sample}$) and the standard ($^{13}C/^{12}C_{standard}$) was analysed by IRMS (Seibersdorf Isotope Laboratory, Vienna). $^{13}C/^{12}C$ value was transformed into $\delta^{13}C$ (‰; per mil) with the help of the following equation.

$$\delta^{13}\mathrm{C}\ (‰) = \frac{(^{13}\mathrm{C}/^{12}\mathrm{C})_{\mathrm{sample}} - (^{13}\mathrm{C}/^{12}\mathrm{C})_{\mathrm{standard}}}{(^{13}\mathrm{C}/^{12}\mathrm{C})_{\mathrm{standard}}} \mathrm{x}1000 \quad (7)$$

The standard used to evaluate the carbon is the PDB (Pee Dee Beliminate). PDB standard is the CO_2 isotope ratio obtained from the Belemnite limestone present in the Peedee formation in South Carolina [16]. $\delta^{13}C$ values is transformed into the carbon isotope discrimination/difference (Δ) using the equation developed by Farquhar et al. [17].

$$\Delta(‰) = \frac{\delta^{13}\mathrm{C_a} - \delta^{13}\mathrm{C_p}}{1 - \delta^{13}\mathrm{C_p}/1000} \quad (8)$$

where a and p in the equation indicates the isotopic ratios of air and plant, respectively. In the formula, a ‰ value of 8 was used for air while transforming the $\delta^{13}C$ value into Δ [18].

3.9.2.1. Carbon isotope ratio of leaves

Values obtained from the leaf carbon isotope (ΔL; ^{13}C‰) ratios are provided in Table 13.

TABLE 13. CARBON ISOTOPE RATIO OF THE LEAF SAMPLES, ΔL (^{13}C‰)

Years	Treatments	$\Delta^{13}C$ – Leaf (‰)
2009–2010	I_1	19.81^a
	I_2	20.09^a
	I_3	19.85^a
	I_4	19.99^a
2010–2011	I_1	19.10^a
	I_2	19.97^a
	I_3	19.46^{ab}
	I_4	19.91^b

According to the variance analysis applied on the carbon isotope ratios ΔL that was determined in the wheat leaves according to the treatments, no statistical difference was found between the treatments in the first year while there was a difference at the 0.05 level in the second year. Variance analysis is provided in Table 14.

TABLE 14. VARIANCE ANALYSIS TABLE FOR THE CARBON ISOTOPE RATIO OF THE LEAF SAMPLES (ΔL)

Years	Variation Source	D.F	S.S	M.S	F	Table F	
						0.05	0.01
2009–2010	Blocks	3	3.8	1.3	3.34	3.86	6.99
	Treatments	3	0.2	0.1	0.56	3.86	6.99
	Error	9	3.4	0.4			
	General	15	7.4				
2010–2011	Blocks	3	0.8	0.3	1.41	3.86	6.99
	Treatments	3	2.0	0.7	10.48*	3.86	6.99
	Error	9	1.7	0.2			
	General	15	4.6				

The Duncan test classifications made for ΔL values were provided in Table 14. According to the results of Duncan test, all the treatments belonged to a single group in year 2009–2010. For the year 2010–2011, the I_2 and I_4 treatments belonged to the first group, while I_3 treatment the second group and the I_1 treatment the third group. In the evaluation made by combining the years, no group difference appeared between the treatments and all the treatments were found to be in the first group. According to the Duncan classification, the irrigation did not have a significant effect on the wheat ΔL value. It can be said that it generated from the fact that the soil moisture did not fall low enough to cause difference between the treatments that were less irrigated compared to no- and full-irrigation treatments at the dates when sampling was made for the carbon analysis (second week of May).

3.9.2.2. Carbon isotope ratio of grains

Values obtained from the results of the carbon (ΔG; ^{13}C‰) analysis made on the grain samples taken during harvest are provided in Table 15.

TABLE 15. CARBON ISOTOPE RATIO OF GRAIN SAMPLES, ΔG

Years	Treatments	$\Delta^{13}C$ - Grain (‰)
2009–2010	I_1	17.94
	I_2	17.99
	I_3	18.47
	I_4	17.96
2010–2011	I_1	17.54
	I_2	18.04
	I_3	17.76
	I_4	18.44

Variance analysis for the carbon isotope ratios ΔG for the grain samples are given in Table 16.

TABLE 16. VARIANCE ANALYSIS FOR THE CARBON ISOTOPE RATIOS (ΔG) OF THE GRAIN SAMPLES

Years	Variation Source	D.F	S.S	M.S	F	Table F	
						0.05	0.01
2009–2010	Blocks	3	1.0	0.3	0.50	3.86	6.99
	Treatments	3	0.8	0.3	1.22	3.86	6.99
	Error	9	5.8	0.6			
	General	15	7.5				
2010–2011	Blocks	3	4.4	1.5	1.58	3.86	6.99
	Treatments	3	1.8	0.6	1.95	3.86	6.99
	Error	9	8.4	0.9			
	General	15	14.6				

As apparent from the variance analysis, no statistical difference was found between the treatments for both years with respect to grain carbon isotope ratios ΔG.

3.10. Association of the results

3.10.1. The relationship between grain yield, biomass and harvest index and water use efficiency

For each year, grain at harvest and biomass yields for the various treatments was evaluated, and a significant and positive relationship was found between grain yield and biomass. The harvest index percentages were calculated using the yield and biomass data (harvest index = [grain yield / biomass] x 100) and a positive relationship was found between them. When each treatment was considered separately, the most significant relationship was obtained in the rainfed treatment (Fig. 12).

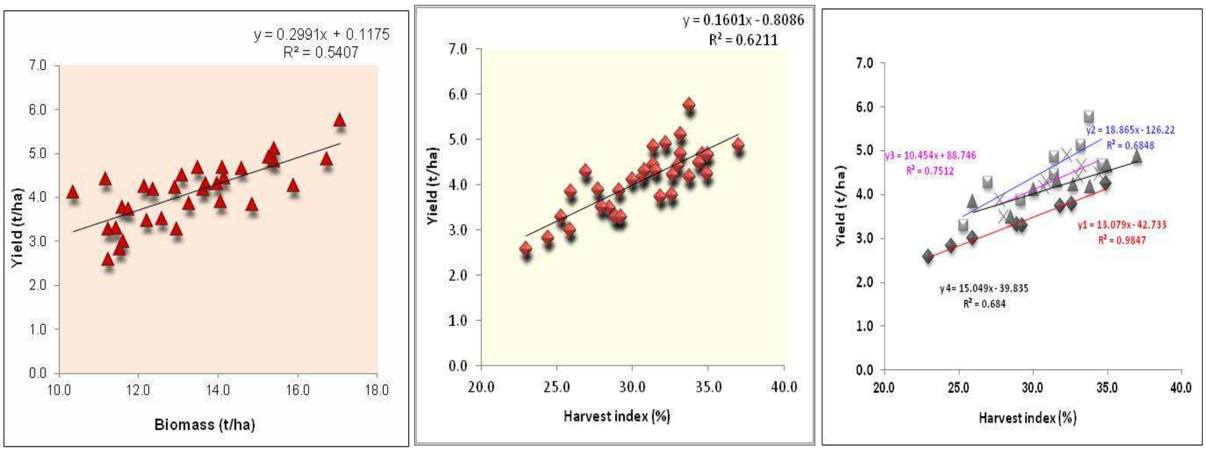


FIG. 12. The relationship between grain yield, biomass and harvest index.

A positive and significant relationship was found between wheat yield and water use efficiency and each increase in WUE led to greater increase in yield in the I_4 (no irrigation until heading period) treatment (Fig. 13).

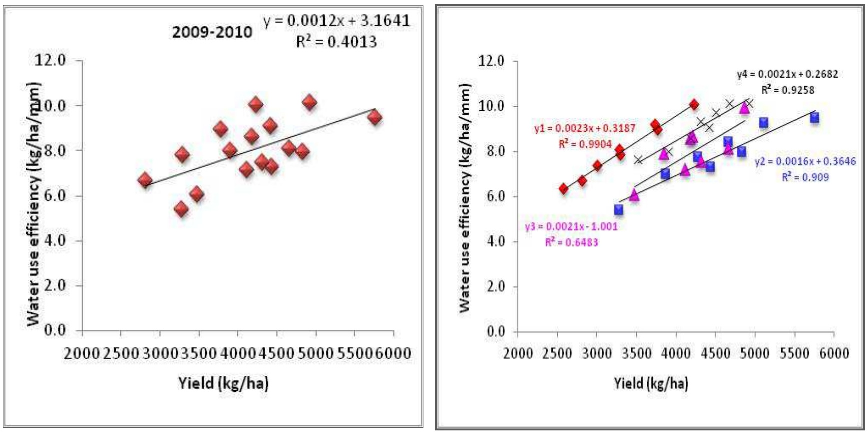


FIG. 13. The relationship between grain yield and water use efficiency.

3.10.2. The relationship between oxygen isotope ratios, yield and water use efficiency

A significant (R^2 = 0.55) and negative relationship was found between the oxygen isotope ratio of grain and grain yield. When the oxygen amount of the plant increased, the yield also increased (Fig. 14).

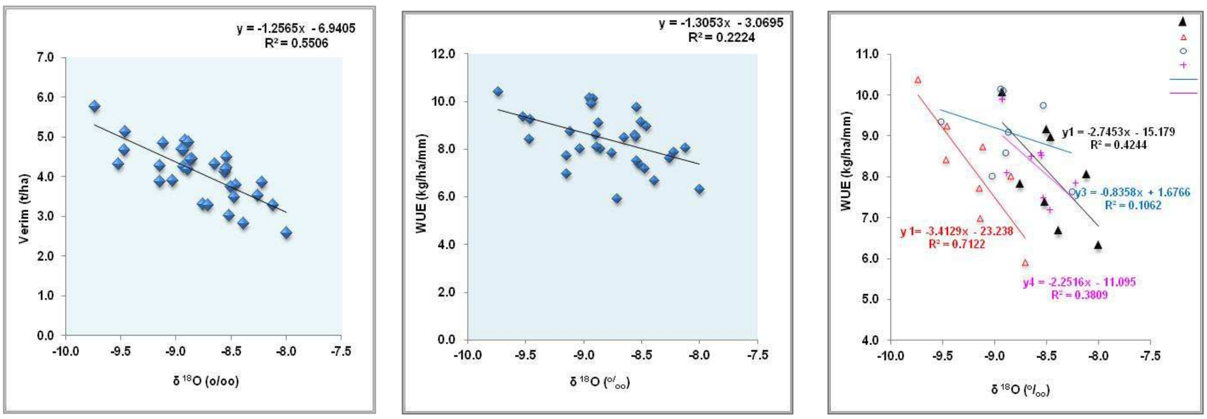


FIG. 14. The relationship between oxygen isotope ratios of grain and yield and WUE.

In the evaluation made for the oxygen percentage of plant and the water use efficiency (WUE) taking into consideration all the plots, the relationship level appeared to be insignificant and their relationship were found to be negative. When the plots are handled individually, the relationship between the oxygen ratio and the water use efficiency of the full-irrigation plot were found to be at a significant level ($R^2 = 0.71$).

3.10.3. The relationship between the leaf and grain carbon isotope discrimination value (Δ) and yield, water use efficiency and $\delta^{18}O$

A positive and significant relationship was found between the leaf and grain carbon isotope discrimination (Δ) and the yield. For each plot, the leaf $\Delta^{13}C$ yield relationship and grain $\Delta^{13}C$ yield relationship are provided in Fig. 15.

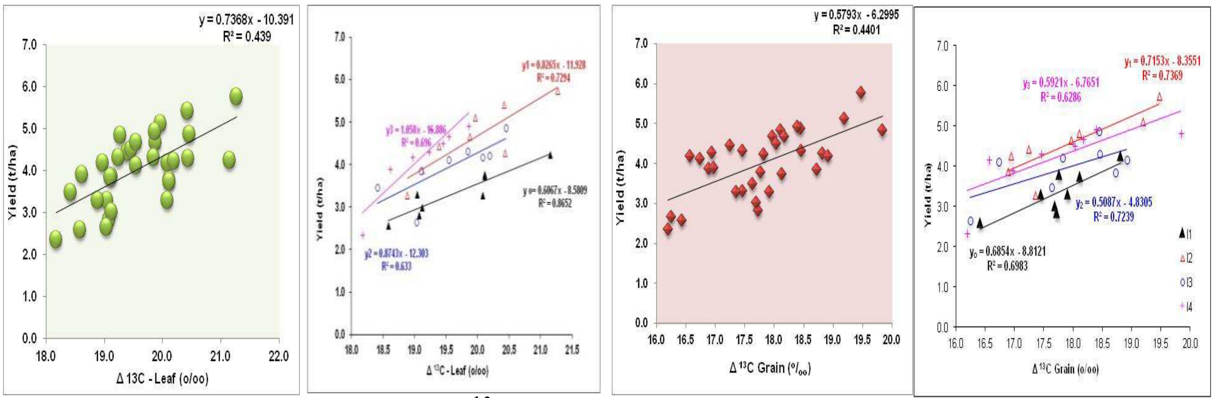


FIG. 15. The relationship between $\Delta^{13}C$ values of leaves and grain and yield.

When the plots are considered separately, it is seen that there is a significant and positive relationship between the leaf $\Delta^{13}C$ and the yield. A positive relationship was found between the yield and $\Delta^{13}C$ under most climatic conditions [19] [20] [21]. In the studies conducted generally under the Mediterranean conditions, a significant and positive relationship was found between the yield and grain $\Delta^{13}C$ and leaf $\Delta^{13}C$ under the conditions of stress [22], [23].

In some studies conducted on wheat, a positive relationship was found between yield and Δ while a negative relationship was found in the other studies. The relationship between Δ and yield can be either positive or negative according to the tissue and gene source of the leaf analyzed, sampling time and water regime [24] [20]. In the samples taken from wheat after anthesis, a positive and significant relationship was found between Δ and yield [25] [23]. It was found that the relationship between grain Δ and yield in the pre-anthesis period, under the water stress conditions depends on the soil moisture during the sowing period and the amount and distribution of the precipitation falling during the growth period [21]. It is reported by Condon et al [26] that the relationship between the Δ of leaf and the yield is usually negative and insignificant under the full-irrigation conditions. According to another study, there is a negative relationship between wheat yield and grain Δ ($R^2 = 0.78$) when the soil water content field capacity is 40%, 70% and 100%, [27].

Under different water conditions, $\Delta^{13}C$ is one of the simple, direct, and effective methods in determining the water use efficiency (WUE) of plants. The relationship between grain and $\Delta^{13}C$ of the leaf and the WUE values determined in the trial is given in Fig. 16. A negative relationship was found between the water use efficiency and $\Delta^{13}C$ values of both leaf and grain.

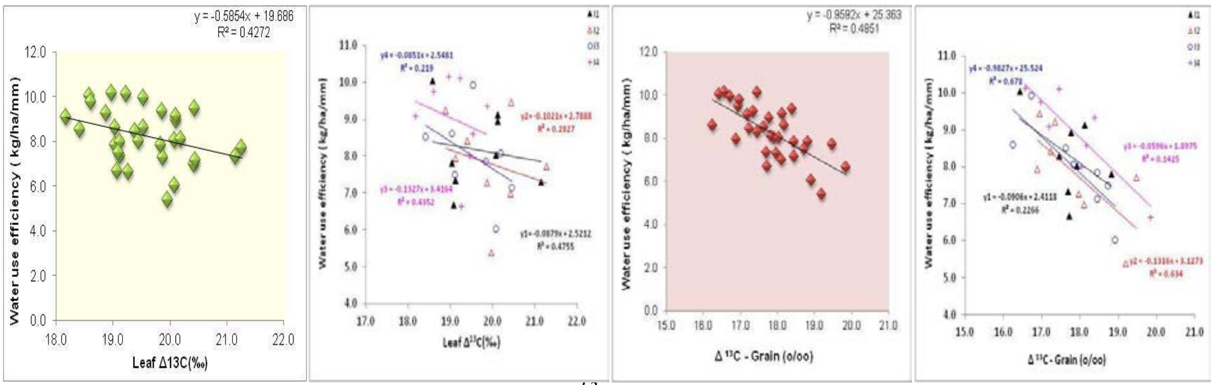


FIG. 16. The relationship between $\Delta^{13}C$ values of leaves and grain and WUE.

However, the relationship level between the grain carbon ratio and the yield was found to be low. When each plot was analysed separately, the relationship between the WUE and carbon appeared to be negative but the relationship level was found to be insignificant (Fig. 16). The relationship between the WUE and Δ of wheat was found to be negative [28] [29].

When the relationship between oxygen ($\delta^{18}O$) and carbon ($\Delta^{13}C$) was analyzed, it was seen that there was a negative relationship between them however the significance level appeared to be quite low (Fig. 17).

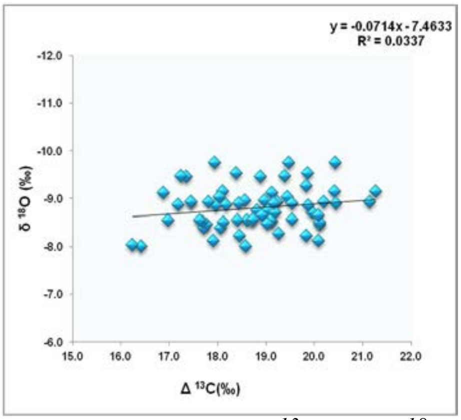


FIG. 17. The relationship between $\Delta^{13}C$ and $\delta^{18}O$ ratios of plant.

In a study conducted on the different wheat varieties for the relationship between $\delta^{18}O$ and $\Delta^{13}C$, a positive relationship was found between the average oxygen and carbon isotope ratios (Barbour et al., 2000) [34]. In addition, when different studies conducted on plants other than wheat were examined, for example; in the studies performed on grass, a negative relationship was found between some grass varieties while there was a positive relationship between some other grass varieties [30]. A positive relationship was also found between the oxygen and carbon isotope ratios of beech and pine trees [31].

$\Delta^{13}C$ ratio of the plant is known to be negatively correlated with CO_2 entering and leaving the leaf [32]. Stomatal opening and closing causes changes in the CO_2 diffusion of plants depending on the environmental conditions thus the $\Delta^{13}C$ and $\delta^{18}O$ ratios of the plant change. It is possible to reveal a clear relationship between the plant carbon and oxygen isotope ratios when studied in controlled environments (greenhouse, climate chamber, etc.) while it is mostly impossible to determine such relationship under land conditions [31] [33] [34] [35].

3.10.4. The relationship between the stomatal conductance and yield, water use efficiency, $\delta^{18}O$ and $\Delta^{13}C$ values

A positive and significant relationship was found between the stomal conductance and the yield. The transpiration ratio increased upon the increase in the stomatal conductance and that increase reflected on the yield (Fig. 18).

In the studies conducted on the relationship between wheat grain yield, photosynthetic rate and stomatal conductance, a significant-positive relationship was found between the yield and stomatal conductance [36] [37] [38].

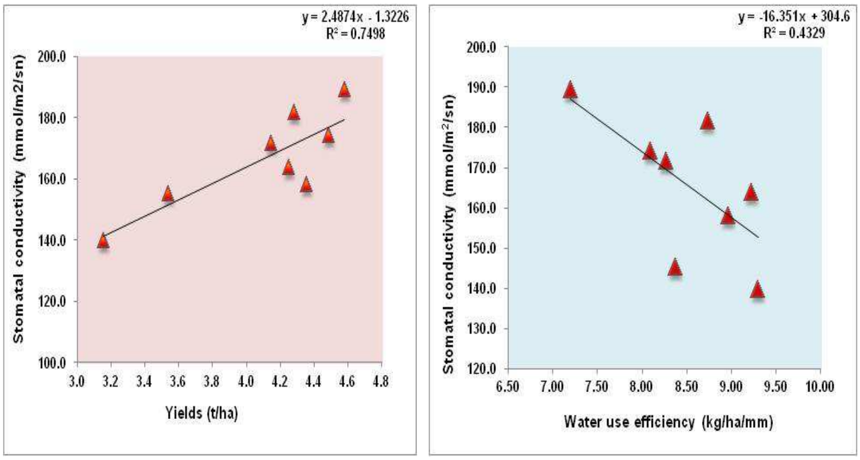


FIG. 18. The relationship between stomatal conductance and yield and water use efficiency.

The water use efficiency at the vegetation level is defined as the proportion of the plant yield per unit area against the level of total water (ET) used by the plants in this area. The total water amount used by the plant includes the stomatal closing that is directly affected by the increase in CO_2 but that can change due to the vegetation cover and plant water intake. Another change appearing in the hydrological regime under the increased CO_2 conditions is the water balance interaction occurring based on the expansion of leaf area. It would cause significant impacts on arid environments which cause direct evaporation from the vegetation cover. Thus, more complex relations and effects appear on the water use efficiency at the level of vegetation [39].

A non-sigficant negative relationship was observed between stomatal conductance and yield and water use efficiency calculated using ET values. As the stomatal conductance decreased, the water use decreased thus the water use efficiency increased.

According to the theory, the $\delta^{18}O$ ratio of the plant material is an indication of the evaporative status of the material therefore the change in the stomatal conductance should show the $\delta^{18}O$ change in the plant [40] [41] [42][32].

The result of the study also showed a negative relationship between the stomal conductance and oxygen isotope ratio, with significance level high ($R^2 = 0.55$) (Fig. 19). In a study conducted by Barbour et al [34] on wheat (*Triticum aestivum L.*), a positive and significant relationship was found between oxygen isotope and stomatal conductance.

When the results of stomatal conductance and $\Delta^{13}C$-Leaf (‰) were evaluated, a significant positive relationship was found between them (Fig. 19). Similarly, in a study conducted by Condon et al [43] on wheat, a positive and significant relationship was found between carbon isotope and stomal conductance.

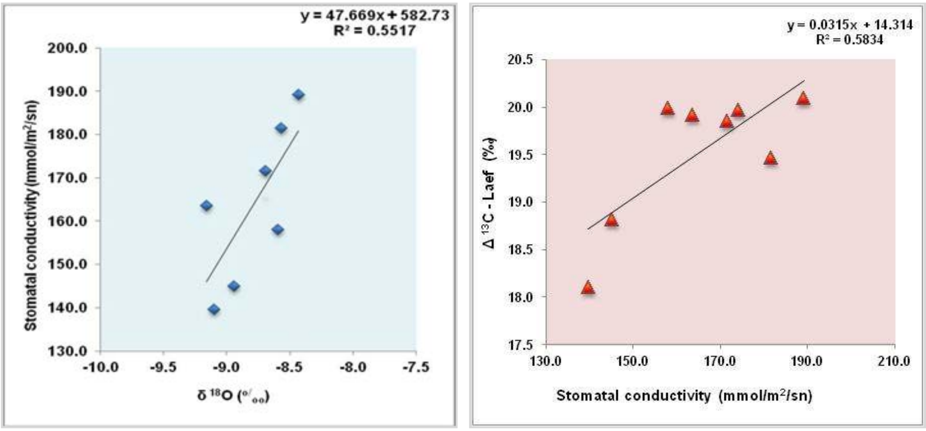


FIG. 19. The relationship between stomatal conductance and $\delta\ ^{18}O$ and $\Delta^{13}C$ ratio of plant.

3.10.5. The relationship between the CWSI and yield, water use efficiency, $\delta^{18}O$ and $\Delta^{13}C$ values

Strong linear correlations were measured among CWSI with grain yields. Grain production was negatively correlated to increasing average CWSI with correlation coefficients of r = –0.851. Highest grain production occurred at no water stress condition with CWSI at 0.24 and 0.42 units in 2009–2010 and 2010–2011, respectively. Irrigations should be scheduled at lower CWSI values to increase irrigation frequency and water applied thereby decreasing WUE with a concurring decrease in grain production. Singh et al [44] also reported similar decreases in WUE with increasing irrigation frequency. Relationship between grain yield, WUE and stomatal conductivity were given in Fig. 20.

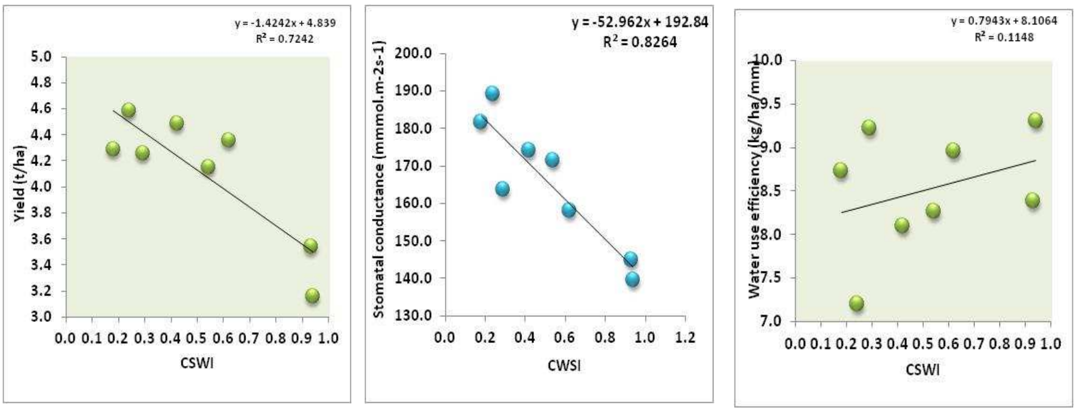


FIG. 20. Relationship between CWSI and grain yield, WUE and stomatal conductivity.

When the relationship between CWSI and $\Delta^{13}C$-Leaf & Grain (‰) were analyzed, it was seen that there was a negative relationship between them however the significance level appeared to be low. However high linear positive correlation was found among CWSI to green canopy cover (CC) with correlation coefficient r = 0.944 (Fig. 21).

The use of infrared thermometers to quantitative water stress of wheat using crop water stress index can be a useful tool in assisting the irrigation manager in irrigation scheduling decisions.

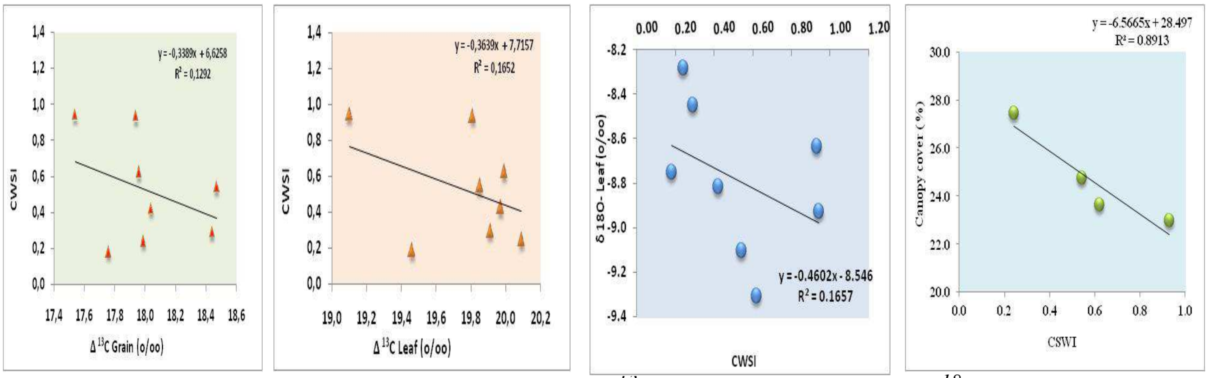


FIG. 21. Relationship between CWSI Δ^{13}C-Leaf & Grain, Leaf δ^{18}O and CC.

4. CONCLUSION

This study conducted during the wheat growth period for the years 2009–2010 and 2010–2011 and 2011–2012 showed that, on average wheat yield was found to be 3.35 t/ha, 4.54 t/ha, 4.22 t/ha and 4.31 t/ha respectively according to the treatments (I_1, I_2, I_3, I_4). The highest yield was obtained from the full-irrigation treatment while the lowest yield was obtained from the no-irrigation treatment. No statistically significant difference was found between the treatments subjected to the irrigation while a difference of $P<0.05$ was obtained between the no-irrigation and full-irrigation treatments. Average harvest index values were found to be respectively 29%, 31%, 32% 31% and 32% again according to the treatments. The treatment I_4 that was irrigated in the same way after the period of heading for both years appeared to have the highest value in the water use efficiency. Water use efficiency appeared to increase under limited irrigation conditions due to shrinking of the stoma opening of the C_3 plants in the CO_2 increases [45] [46].

The transpiration ($\%F_T$) and evaporation ($\%F_E$) ratios determined using atmospheric water vapour (δ_{ET}) according to the Keeling plot method, showed that the proportion of transpiration as percent of total ET was between 70.5 to 96% on 5 May while it was approximately 70% on 26 May.

Although there was no statistical difference between the treatments (I_1, I_2, I_3, I_4) in carbon isotope ratio (Δ) of leaves, a significant positive relationship was found between carbon and yield ratios of both grain and leaf, and a significant negative correlation between the water-use efficiency. It demonstrates that it is possible to select wheat varieties with the highest water use efficiency, by using carbon isotope ratios in arid and semi-arid regions [21], [26] [23] [24].

The positive relationship between the stomatal conductance and yield and the increase of the transpiration in environments without any irrigation restriction indicate an increase in plant biomass and yield. A negative relationship was found between the stomatal conductance and oxygen rate of the plant. It can be considered that the amount of water present in leaf would decrease since the amount of water escaping away from the pores ultimately would decrease as the conductance increase.

The relationship between stomatal conductance and yield value was found to be high in the treatments having a high transpiration ratio. However, the increased transpiration ratio reduced the water use efficiency. Although CO_2 used in photosynthesis was expected to increase upon the increase in transpiration amount, no significant relationship was found between Δ^{13}C and δ^{18}O ratio. In the studies conducted on this topic, it is reported that changes appearing in the CO_2 diffusion of the plant depend on the environmental conditions also cause changes in the $\Delta^{13}C$ and $\delta^{18}O$ ratios, therefore it is necessary to study in controlled environments (greenhouse, climate chamber, etc.) in order to reveal a clear relationship between the plant carbon and oxygen isotope ratios, it is mostly impossible to determine such relationship under field conditions [31], [33] [34] [35].

The results presented in this work suggest that the amount of soil water content affects the canopy temperature and stomatal resistance of the crop. CWSI values increased because of the depletion of soil water. When the relationship between CWSI and $\Delta^{13}C$-Leaf & Grain (‰) were analyzed, it was seen that there was a negative relationship between them, however the significance level appeared to be quite low. However high linear positive correlation was found among CWSI to green canopy cover with correlation coefficient r = 0.944. The CWSI is a promising tool for quantification of the crop water stress.

The results obtained from this study indicate that isotopic techniques can be effectively used in the studies on plant water consumption. It will be possible to identify the most appropriate land use and irrigation management strategies in order to minimize the evaporation from the soil, and irrigation programs can be developed to increase the marketable plant yield per unit water consumed by the plant, if the water consumption occurring via transpiration only by the plant is known. Also the evaporation from soil can be prevented and irrigation water can be targeted to just the amount consumed by plants due to knowledge about the plant transpiration. As a result, fertilizer, agricultural chemicals and organic matter losses will be minimized.

Summary of the results:

- The results of this study indicate that carbon isotopic discrimination can be used for estimating WUE under water-limited conditions.
- This result shows that WUE is strongly dependent on stomatal conductance.
- It might be recommended that irrigation concentrated in the after heading period increase WUE of wheat in Central Anatolia Region of Turkey.
- CWSI is a useful tool for detecting crop water stress.
- The results indicated that isotopic techniques can be used to improve plant water consumption and minimize soil evaporation component.

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ENHANCING THE CONTRIBUTION OF ISOTOPIC TECHNIQUES TO THE EXPANSION OF PRECISION IRRIGATION[2]

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Abstract

In the future, irrigated agriculture will take place under water scarcity, as insufficient water for irrigation is becoming the norm rather than the exception. There is a need to increase the precision of water application with irrigation management. Successful application of the precision irrigation (PI) concept requires one to know the crop water requirements with a certain degree of accuracy and to be able to monitor effectively the water status of the root zone. This paper reviews the use of remote sensing from satellites to characterize irrigation performance for benchmarking areas in need of improvement. The use of remote sensing techniques has progressed substantially in recent years through their capability to detect vegetation properties with very high resolution. Similarly, a new approach which uses cosmic-ray neutrons involving measuring background fast neutrons radiation from cosmic rays and those generated within the soil, moderated by hydrogen atoms in water, is showing promise for obtaining information about area-wide temporal changes in water content in relation to satellite remote sensing observations.

Below is a summary of the paper published in [1].

1. INTRODUCTION

Irrigation consumes nearly 70 percent of all freshwater abstractions. With competition from other sectors and diminishing options for developing new supplies, saving water in irrigation is necessary. This can be achieved by engineering method of minimizing conveyance losses by converting open channels to pipe networks, changing the method of irrigation from gravity to pressurized systems (sprinkler or drip). For such potential to be realized only if there is adequate management of water.

To achieve efficient use of water in agricultural systems, science, engineering and management are all needed. Three water resource situations summarized all cases of irrigated production: 1. Water is abundant and reliable supplies are guaranteed, irrigation tends to exceed crop water requirements; in this situation substantial water savings are feasible, 2. Water supplies vary from unconstrained to restricted during periodic droughts, water savings is still possible in years of ample supply and by adopting better coping strategies in drought years, 3. Chronic water scarcity, occurs in many arid and semi-arid areas of the world. The emphasis should be on optimizing the use of the limited supplies by concentrating the available water on high-value crops and by using deficit irrigation [2] in a sustainable fashion.

[2] This paper is a summary of the key points of a full paper presented in the 'Proceedings of an International Symposium on Managing Soils for Food Security and Climate Change Adaptation and Mitigation, 2014'

2. PRECISION IRRIGATION

Precision irrigation (PI) is defined as the efficient, timely and correct amount of water delivered to fields to maximize crop yield and quality, and to minimize environmental impacts, including the application of variable amounts of water over a field in response to spatial crop and soil heterogeneities. For successful application of PI, one needs to know the crop water requirements (ET) and the water status of the root zone.

Irrigation scheduling (IS) i.e. to determine precisely the time and amount of irrigation (Fereres, 1996) [3] using the soil water budget is the first step for optimizing on-farm water management. Information needed such as reference evapotranspiration (ETo) can be calculated from meteorological variables, while crop coefficient (Kc) values for the major water demanding crops have been published [4] and computer programs have also been developed for such purposes. The soil water budget method mentioned above has several uncertainties: 1. the assumptions on the relations between ETo and ETc (crop evapotranspiration), particularly in the case of woody crops, and on the representativeness of the point measurements of soil water considering the spatial variations in soil water across fields, 2. the determination of optimum frequency of irrigation due to different field and irrigation system design characteristics and is difficult to take into account in simple models. The frequency of irrigation is a crucial aspect of irrigation scheduling, determining largely the overall on-farm irrigation efficiency.

New generations of soil water sensors which track soil water status continuously are now available as opposed to the traditional instruments with intermittent measurements. Unfortunately, these new developments have not resolved the quantification of volumetric soil water content with depth, a parameter that is still most reliably measured with the neutron probe, particularly under saline soil conditions [5].

Soil water variability due to variations in soil properties and the non-uniform wetting of localized irrigation made it difficult for point sensors to obtain representative estimates of the soil water content of a whole field. In recent years, with management units size increases in an attempt to reduce production costs, this had created considerable challenges for farmers to manage, as the complexity of the farms increases due to the variability and heterogeinity problems. Significant uncertainty is therefore introduced and often irrigation management decisions have substantial errors.

To advance solutions for coping with the variability problem, it is important to be able to characterize the variation across a field, and to have the option of applying variable amounts of water within that field, i.e. to apply water at variable depths under non-uniform crop growing conditions to match the requirements of every area of the field, while minimizing the environmental consequences arising from uniform irrigation over a variable field. New PI technologies for variable water application such as the self-propelled sprinkler systems which have shown significant water conservation [6] and different pressurized methods, including micro-irrigation [7] are already available, this should enable growers to increase productivity and minimize the negative environmental impacts of irrigation.

Nevertheless, there is still the need to characterize and monitor the variability as well as to interpret the causes of variations in crop growth and development. Remote sensing [8] is a promising area, as it enables performance to be evaluated quickly and inexpensively, and can identify areas in need of improvement. Recent development has enabled the remote sensing techniques to detect a number of vegetation properties with very high resolutio [9], with images obtained from aerial vehicles flying closer to the ground.

3. ISOTOPIC TECHNIQUES FOR PRECISION IRRIGATION MANAGEMENT

Isotopic techniques (using isotopes of water: oxygen-18 and deuterium) can be used to separate evapotranspiration into soil evaporation (E) and crop transpiration (T) to determine the relative magnitudes of E and T in different situations [10, 11]. Such knowledge is important for effective irrigation management.

4. ASSESSING SOIL WATER OVER LARGE AREAS: THE COSMIC-RAY NEUTRON PROBE (CRNP)

The cosmic-ray neutron probe [13, 14] is a relatively new instrument that can provide 'area-average' soil water content over a radius of 300 m and to a depth of 70 cm [13, 15, 16]. This allows the integration of variations caused by differences in soil–crop properties and in the distribution of irrigation water for the computation of the components of the field water balance if the appropriate inputs and outputs are recorded.

The possibility of characterizing the variation across a field and applying variable amounts of water within that field can help to advance solutions for coping with the variability problem. Also, instead of basing irrigation on averaging field indicators and integration of some farm constraints, sub-field areas with 'uniform' characteristics should be considered where they are watered differentially from others.

5. CONCLUSIONS

An integrated approach involving the use of remote sensing, field and large-scale soil moisture sensing devices such as the soil moisture neutron probe and the new cosmic-ray neutron probe method is needed to improve the application of PI for accurate determination of area-wide crop water requirements and the water status of the root zone. The new PI capabilities should enable growers to evaluate performance in a fast and inexpensive way, leading to increased productivity and to reduce environmental impacts of irrigation.

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SIMULATING YIELD RESPONSE OF WHEAT (TRITICUM AESTIVUM L.) TO DEFICIT AND REGULATED DEFICIT IRRIGATION UNDER SEMI–ARID CONDITIONS USING AQUACROP MODEL

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Abstract

Scarcity of irrigation water in Pakistan warrants the adoption of appropriate practices to minimize crop water use for maximizing crop water use efficiency (WUE). This study was carried out to enhance WUE and optimize irrigation scheduling for optimal wheat yield under water scarce conditions. Field experiments with different irrigation regimes: rain–fed, optimal irrigation and regulated deficit irrigation at different growth stages were conducted on a deep loam soil for six crop seasons (2008–09 to 2013–14). The results showed that regulated deficit irrigation at less sensitive crop stage(s) could allow up to 25 percent water saving without compromising economic yield. AquaCrop simulations were able to simulate crop development (canopy cover and in–season biomass), crop yield, soil moisture dynamics and water productivity under different irrigation regimes and can be a useful tool for assessing crop requirements and devising irrigation strategies to enhance water productivity under different scenarios.

1. INTRODUCTION

The fundamental characteristic of arid to semi–arid climate of Pakistan is that annual evaporative losses of water from the soil surface are higher than the precipitation. Due to the resulting water deficiency there is a heavy reliance on irrigation from Indus River System (IRS) to maximize crop production [1] [2]. The mean quantity of water entering IRS is about 187 billion cubic meters (BCM), of which 128 BCM is diverted at the canal heads. However, the overall agricultural use–efficiency of this water is unfortunately very low due to losses during conveyance to farm–gate and improper irrigation practices. Further, the availability of irrigation water is not consistent and fluctuates greatly for crop seasons as well as each year. During 2008–09 Rabi (winter crops) season, the estimated water availability was 31 BCM, which remained 31.6 percent less than the normal availability and 10.7 percent less than the previous (2007–08) year’s Rabi. This water deficiency is met with groundwater abstraction (about 50 BCM per year) with a consequent depletion of groundwater at an alarming rate. The shallow groundwater of good quality is found merely along canals or rivers as narrow belts. In areas away from rivers and canals, the groundwater is saline but the farmers are compelled to pump it to meet irrigation requirements of crops. A continuous use of such poor quality water leads to soil degradation that affects the crop yields and creates serious problem of salinization of productive land.

Like elsewhere in the world, competition for water among agriculture, industrial and urban sectors is increasing in Pakistan. The agriculture sector is most likely to be a loser in this competition because of lower economic productivity of water in agriculture (value per liter) than in the other sectors. Use of water in Pakistan agriculture is wasteful with alarmingly low water productivity. Irrigation can be made more efficient by changes in water management strategies at all levels.

Better irrigation management is important for increasing crop water use efficiency (WUE), enhancing yield and minimizing any adverse environmental impact. Higher WUE can be achieved by maximizing crop water productivity using efficient irrigation techniques such as drip and deficit irrigation, the latter has not received sufficient attention in research [2]. With this practice, reductions in the quantity and timing of irrigation may save water without reducing significantly the quantity or quality of the crop yield. Geerts and Raes [3] reviewed selected research from around the world covering a range of crops and summarized the advantages and disadvantages of deficit irrigation; and it has been demonstrated successfully and widely used in Andalucia Spain [4].

Deficit irrigation requires accurate estimation of potential crop evapotranspiration (ETc), which is difficult to compute accurately without computer models [5]. The FAO AquaCrop model has the ability to separate deep percolation, evaporation and transpiration components of the total water budget during a crop growing season. The model simulates crop yields as a function of water consumption [6] and is an important tool for estimating crop water productivity under different irrigation management strategies for improving WUE in agriculture [7] [8].

Very little research on deficit irrigation has been carried out in Pakistan. The purpose of this study was, therefore, to evaluate irrigation techniques on wheat yield and WUE and to devise strategies for water saving without compromising crop productivity using simulation modelling approach.

2. MATERIALS AND METHODS

2.1. Study area

This study was conducted at the experimental farm of the Nuclear Institute for Agriculture and Biology (NIAB), Faisalabad, Pakistan (31°23' N, 73°2' E, 184 m asl). The area features a semi–arid climate (BWh) in Köppen–Geiger classification characterized by large seasonal variations for both temperature and precipitation. Study period and historic daily climatic data (1974–2014) was collected from metrological observatory of Pakistan Meteorological Department (PMD) operating adjacent to the study site. The average monthly maximum and minimum temperature (^{o}C) and rainfall (mm) during wheat growing months (2008–14) along with long term averages (1974–2014) at the study site are given in Fig. 1. Average minimum temperature (T_{min}) during the study period was similar to the normal T_{min} (10 ^{o}C) recorded for this region. Averaged across the 6–year study period, the mean T_{min} from November, December, January, February, March and April was 11, 6, 4, 8, 14 and 19 ^{o}C, respectively; whereas the normal mean T_{min} for these months is 11, 5, 4, 6 13 and 18 ^{o}C, respectively. Compared to the normal mean maximum temperature (T_{max}) for the wheat growing months in Faisalabad, the mean T_{max} remained 1– 2 ^{o}C higher in the present study.

The study area receives rainfall (P) from both South–Asian monsoon and western disturbances giving a twin peak type distribution. Mean annual P is around 400 mm with comparatively higher events concentrated in four summer months (June to September). Wheat growing season P, which is 20–25 percent of the total rainfall, is associated with western disturbance producing about 90 mm. The study period (2008–14) means annual P (50 mm) was lower than the long term average. Mean annual P in the months of initial phases of crop growth (November–January) was negligible. Slightly higher rainfall of 18 and 12 mm was

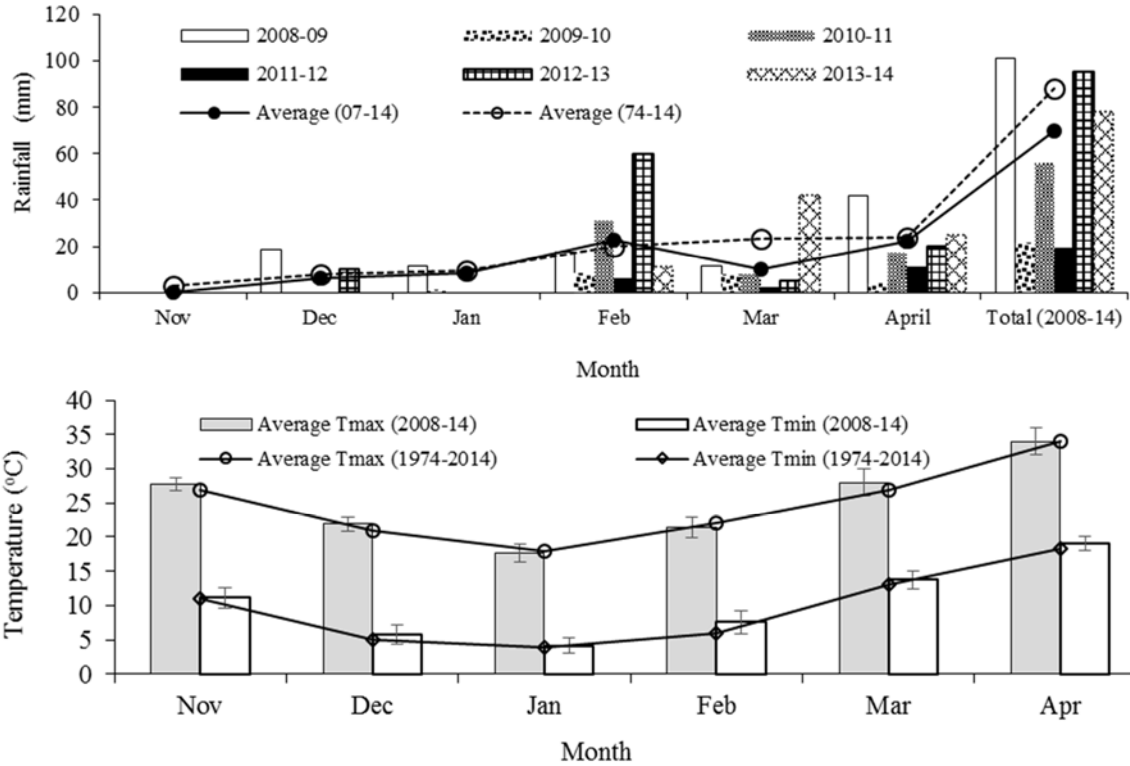

FIG.1. Average monthly maximum and minimum temperature (°C) and rainfall (mm) during wheat growing months (2008-14) along with long term averages (1974-2014) for Faisalabad, Pakistan.

recorded in the months of December 2008 and January 2009, respectively. On average, the growing season P was 100, 22, 56, 19, 95 and 78 mm during crop growing season from 2008–09 through 2013–14.

Soil of the study site is Himalayan alluvial, loam texture, alkaline calcareous, poor in organic matter (<1 percent) and total nitrogen (<0.05 percent), classified as Aridisol, mixed, hyperthermic Ustalfic, Haplargid based on the USDA soil classification system and Haplic Yermosol according to the FAO classification system. Minimum soil characteristics data required as input parameters for the AquaCrop model is presented in TABLE 6.

TABLE 6. PHYSICAL–CHEMICAL CHARACTERISTICS OF THE SOIL AT STUDY SITE USED FOR AQUACROP CALIBRATION AND EVALUATION

Soil depth m	Clay %	Silt %	Sat %	ρb	EC $_{(1:1)}$ dS/m	pH	θ_{FC}	θ_{PWP}
0–0.15	27	32	48	1.56	0.48	8.25	0.29	0.11
0.15–0.35	24	37	47	1.40	0.35	7.96	0.28	0.10
0.35–0.55	20	35	46	1.39	0.41	8.08	0.23	0.11
0.55–0.75	20	34	46	1.43	0.46	8.19	0.27	0.11
0.75–1.05	20	34	45	1.55	0.5	8.13	0.27	0.10

2.2. Experimental design and crop management

Field experiments were carried out during six crop seasons 2008–09 to 2013–14, to determine the yield and WUE of wheat (Triticum aestivum L.) under varying irrigation water applications. Detailed description of experimental design, seeding and fertilizer application is given in [9]. The crop performance data (yield and water use efficiency) for all irrigation treatments for the seasons 2010–11 to 2013–14 is presented here.

AquaCrop calibration was carried out with the data obtained from 2008–09 crop which was grown under unstressed soil moisture conditions, i.e. irrigation application at four growth stages (I–I–I–I) including crown root initiation/tillering, booting, flowering and grain formation. To evaluate the performance of the model under soil moisture stressed conditions, rain–fed treatment (O–O–O–O) was included in the study years 2009–10 and 2010–11. Thereafter, alongwith I–I–I–I and O–O–O–O treatments, the model was furtehr evaluated for its ability to simulate crop performance under regulated deficit irrigations: 50 percent irrigation at the booting stage (I–0.5I–I–I), at grain filling (I–I–I–0.5I), and at both booting and grain filling stages (I–0.5I–I–0.5I).

2.3. Crop evapotranspiration (etc)

Crop evapotranspiration (ETc) was calculated using water balance approach using the equation $(I + P \pm \Delta S) = ETc + (R + D)$, where, I and P represent irrigation and rainfall, respectively. Drainage (D) of irrigation water below the root zone was measured by two Passive–wick fluxmeters installed at 1 m and 1.25 m soil depths in I–I–I–I treatment, connected to a data logger for direct monitoring of drainage.

Soil moisture depletion (ΔS) was calculated by subtracting volumetric moisture content (θv) in the soil profile (0–95 cm) at maturity from that at crop planting. Both, the soil moisture at crop planting and maturity were measured gravimetrically and converted to θv from each treatment plot. To assess the changes in soil moisture content in the root zone during active crop growth period for irrigation scheduling, moisture status at different soil depths was measured using on–site calibrated neutron moisture meter (NMM) [8].

2.4. Aquacrop calibration and evaluation

Reference crop evapotranspiration (ETo) was estimated using the ETo calculator (Version 3.1) developed by FAO by using the weather data obtained from PMD. As crop development stages in AquaCrop were defined when 50 percent of the plants showed visual signs of the stage, 10 plants from each treatment and replicate were tagged after crop emergence to study/record the development stages as number of days taken from emergence to: (i) tillering; (ii) anthesis; (iii) end flowering; (iv) senescence; and (v) physiological maturity.

Aboveground biomass was determined at different growth stages by clipping the plants at soil surface within a 1 m x 1 m area in each treatment plot. The corresponding canopy cover (CC percent) was monitored using digital photographs. The photographs were taken high enough (1–1.5 m) above the canopy at mid–day and digitized using a JAVA program (Image–J) for calculation of canopy cover. Built–in values for initial canopy cover and water productivity were used. Soil fertility and salinity stresses for biomass production were not considered. From the biomass, grain yield and soil water balance, water use efficiency based on biomass (WUE_b) and grain (WUE_g) were calculated.

Default values for canopy cover per seedling, water stress factor for canopy expansion, soil depth contributing to seed germination, deepening shape factor and mid–season crop coefficients were used.

Simulation performance of AquaCrop was evaluated by calculating different statistical indices including root mean square error (RMSE) [10], normalised root mean square error (NRMSE) and by an index of agreement (d) [11]. These parameters were calculated as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}[S_i - M_i]}{n}} \tag{1}$$

$$\mathrm{NRMSE} = \sqrt{\frac{\sum_{i=1}^{n}(S_i - M_i)^2}{n}} \times \frac{100}{M} \tag{2}$$

$$d = 1 - \frac{\sum_{i=1}^{n}[M_i - S_i]^2}{\sum_{i=1}^{n}[|S_i - \bar{M}| + |M_i - \bar{M}|]^2} \tag{3}$$

where Si and Mi = predicted and measured values for variables studied; and n = number of observations. Linear regression analysis between simulated and observed grain yield and biomass at harvest was conducted to evaluate the performance of the model. Model performance improved as R^2 and d values approach unity while RMSE values are nearer to zero.

3. RESULTS AND DISCUSSION

3.1. Biomass and grain yield at harvest

Analysis of variance (ANOVA) for biomass and grain yield at harvest indicated significant ($p \leq 0.05$) effect of deficit/regulated deficit irrigation in all study years (Fig. 2). Averaged across growing seasons, highest reduction (23 percent) in aboveground biomass was recorded when irrigation was skipped at crown root initiation stage. The overall reduction was relatively less (11–12 percent) when moisture stress at late vegetative or at flowering stage was imposed, whereas minimum reduction (8 percent) was recorded for moisture stress after flowering stage stage. Applying regulated (50 percent) deficit irrigation at booting stage compensated 35 percent of the biomass reduction caused by missing full irrigation. Regulating deficit irrigation (50 percent) after flowering showed almost similar biomass yield as recorded with fully irrigated treatment, or when the same irrigation was fully skipped. However, applying two regulated deficit irrigations (at booting and after flowering) showed lesser reduction in biomass (10 percent) compared to fully skipped irrigation at crown root initiation stage (23 percent reduction).

Similarly, averaged across study years, highest (20 percent) reduction in the grain yield was recorded when irrigation was skipped at early crown root initiation stage, i.e. first irrigation after planting ($p \leq 0.05$). Soil moisture stress at booting, at flowering or at late maturity stages resulted in 8–12 percent lower yield compared to unstressed conditions. None of the regulated deficit irrigation treatments could produce grain yield at par with the unstressed treatment with overall reduction in grain yield from 7–10 percent.

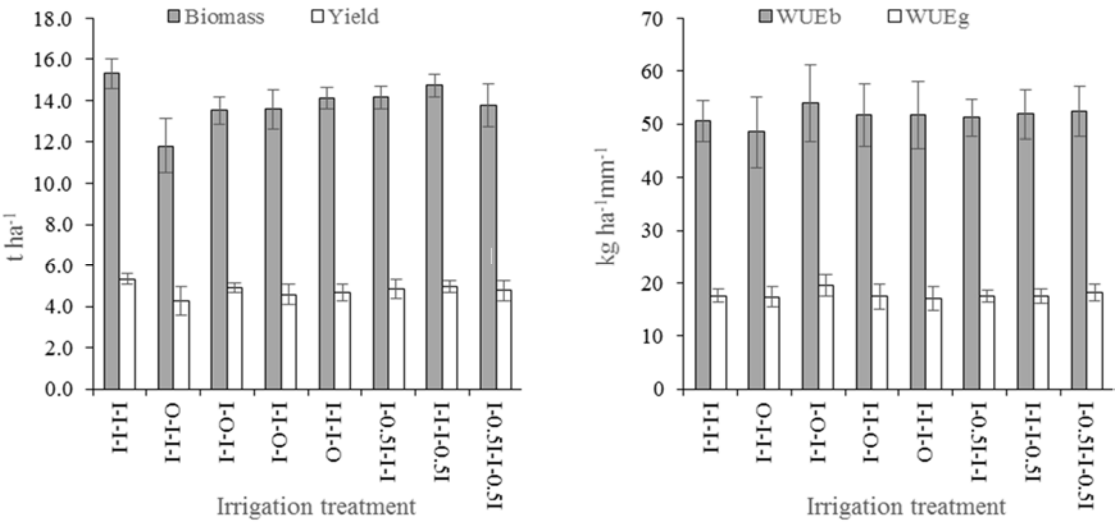

FIG. 2. Biomass, grain yield, water use efficiency based on biomass and grain yield of wheat under different irrigation treatments [*values are mean±SD*] *of four wheat growing seasons from 2010-11 to 2013-14.*

3.2. Water use efficiency

The data measured for biomass, grain yield and seasonal crop ETc was used to calculate water use efficiency for biomass (WUE_b) and grain (WUE_g) production (Fig. 2.). The mean WUE_b under unstressed treatment was 51±4 kg/ha/mm whereas it was lowest (48±7 kg/ha/mm) when irrigation was skipped at crown root initiation stage. The overall increase relative to the control was highest (7 percent) when irrigation was skipped at booting stage of the crop. Moreover, all deficit and regulated deficit irrigation treatments had 1–4 percent higher WUE_b compared to the control. However for WUE_g, most of the deficit and regulated deficit irrigation treatments had lower values (1–3 percent) comapared to the control (18±2 kg/ha/mm) except when irrigation was skipped at booting and regulated deficit at booting and grain formation simulataneously having 11 and 3 percent higher WUE_g.

3.3. Aquacrop simulations

3.3.1. Model calibration

The FAO AquaCrop Model was calibrated using the measured 2008–09 non–stressed irrigated treatment (canopy cover, biomass and grain yield) of wheat, and was subsequently used to simulate data from the 2009–2011 seasons. Fig. 3 showes selected results from the simulations.

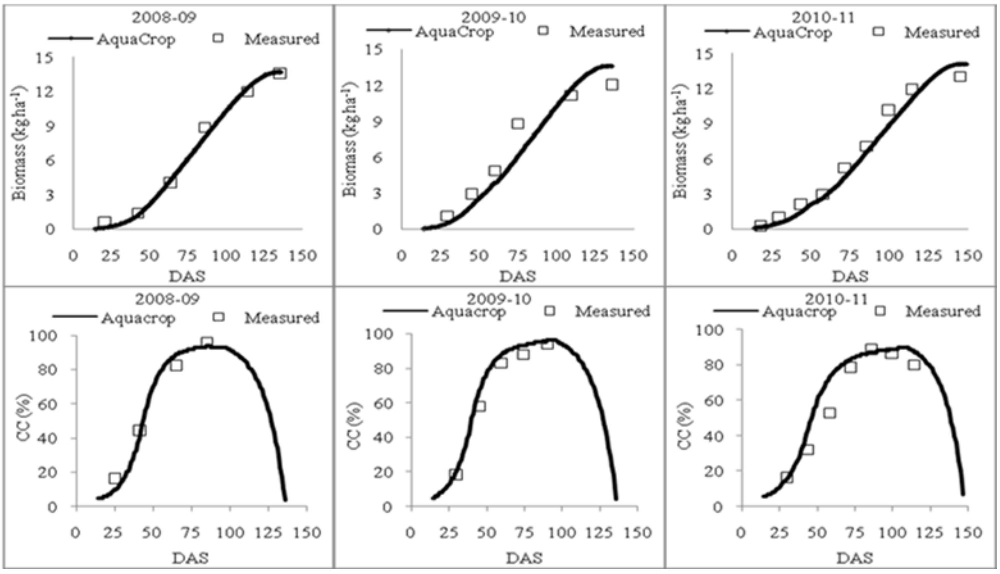

FIG. 3. Measured and simulated (AquaCrop) in–season biomass and canopy cover (CC) of irrigated wheat for both calibration (2008–09) and validation of the model (2009–10, 2010–11).

3.3.2. Soil water dynamics

The model performance to simulate distribution of volumetric moisture (θv, m/m) among different soil layers viz. 0–15, 15–35, 35–55, 55–75, 75–95 cm and total soil moisture (mm) in the root zone (considered as 1 m in this study) during calibration was generally satisfactory (Table 2). The simulated and measured θv in upper 15 cm layer during calibration phase was good (NRMSE 12 percent) and d value of 0.74. Similar results were obtained for 15 – 35 cm soil depth with d, RMSE and NRMSE of 0.80, 0.03 and 11 percent, respectively. However, for deeper soil layer (35 – 55 cm), a lower d value (0.60) with slightly higher RMSE (0.07 m/m) and NRMSE (21 percent) was found. Total soil moisture (mm) within the root zone was simulated well with d index 0.86, RMSE 15 and NRMSE 18 percent. Approximately similar results were obtained during model validation phase in crop season 2009–10 and 2010–11 (Table 2).

TABLE 2. STATISTICAL INDICATORS OF MODEL PERFORMANCE FOR INDIVIDUAL SOIL LAYERS IN DIFFERENT YEARS AND OVERALL SOIL MOISTURE

Depth (cm)	Crop year 2008–09			2009–10			2010–11		
	d	RMSE (m/m)	NRMSE (%)	d	RMSE (m/m)	NRMSE (%)	d	RMSE (m/m)	NRMSE (%)
0–15	0.74	0.03	12	0.85	0.03	12	0.79	0.03	13
15–35	0.80	0.03	11	0.84	0.03	11	0.75	0.03	13
35–55	0.60	0.07	21	0.63	0.04	16	0.68	0.06	19
55–75	0.87	0.04	14	0.75	0.06	17	0.72	0.03	18
75–95	0.84	0.05	16	0.89	0.04	14	0.80	0.04	17
SMC (mm)	0.86	15	18	0.87	13	16	0.75	20	19

3.3.3. Biomass and grain yield at harvest

Table 3 shows the comparison of measured versus simulated biomass (end–season) and grain yield under unstressed conditions, with 1.26 percent deviation for biomass and 0.98 percent for grain yield for calibration year 2008–09. Higher differences in end–season biomass (19.9 percent) for rain–fed and 7.35 percent for irrigated conditions were observed for model validation year 2009–10 particularly at the earlier growth stages. Predicted crop yields can be sensitive to several factors such as soil type, biological, chemical and hydraulic properties of the plant and soil [12],[13]; therefore, comprehensive quantitative soil moisture measurements and rooting chractersitics were needed to analyse plant growth in response to the stressed environment. To account for rooting depth and contribution of soil moisture from deeper soil depths, direct measurements of root growth under field conditions at 20–day intervals were made in the 2010–11 crop season; this allowed the justification of adjusting the maximum root length of 1.2 m at 100 days after sowing (DAS). As a result, smaller percentage deviations in biomass for the irrigated treatment were observed for the crop season 2011–12.

In general, the model simulated crop growth parameters well for irrigated treatments, with some over–estimations of biomass grain yield in rain–fed treatment of growing season 2009–2011 and 2011–2012 (Table 3). For the regulated deficit treatments, some predictions were better than others.

TABLE 3. MEASURED AND AQUACROP SIMULATED VALUES OF BIOMASS AND GRAIN YIELD OF WHEAT UNDER DIFFERENT IRRIGATION REGIMES DURING CROP SEASONS 2008–2012 [9]

Crop	Treatment	Biomass (t/ha)			Grain Yield (t/ha)		
		M*	S	D (%)	M	S	D (%)
2008–09	I–I–I–I	13.51	13.68	1.26	5.10	5.15	0.98
2009–10	Rain–fed	5.83	6.99	19.91	2.10	2.39	13.80
	I–I–I–I	11.98	12.86	7.35	4.68	4.89	4.49
2010–11	Rain–fed	6.07	7.38	19.05	1.89	2.10	4.90
	I–I–I–I	15.30	14.07	–2.53	5.70	5.51	4.97
2011–12	Rain–fed	6.53	7.27	11.85	1.97	2.25	12.50
	I–I–I–I	15.03	13.70	–8.67	5.46	5.42	–1.45
	I–0.5I–I–I	14.20	13.70	–3.52	5.23	5.42	4.23
	I–I–I–0.5I	14.36	13.70	–4.86	5.30	5.42	2.26
	1–0.5I–I–0.5I	14.10	13.69	–2.91	5.13	5.42	6.27

Linear regression analysis of simulated and measured aboveground biomass and grain yield of pooled data reveled significant relationship for biomass (R^2 = 0.98) and grain yield (R^2 = 0.99) (Fig. 3). The slope of regression line (1.25) showed comparatively higher measured biomass growth relative to simulated one. However, the relationship for grain yield was comparatively better with slope of the line 1.1 and intercept 0.4 t/ha.

Since examining yield response to different water applications in field and controlled experiments is laborious and cannot cover all possible combinations of factors influencing crop growth, modelling can be a useful tool to study and develop appropriate deficit irrigation strategies [3], 14].

3.3.4. Water use efficiency

The simulated and the measured water use efficiency (kg/ha/mm) for biomass (WUE_b) and grain yield (WUE_g) of each irrigation treatment and study year (Fig.4) were calculated by dividing simulated and measured biomass and grain yield by respective simulated and measured ETc of each treatment. Measured WUE_b ranged from 55 kg/ha/mm under rain–fed conditions of crop season 2010–11 to 34 kg/ha/mm in unstressed conditions of crop seson 2009–10. Generally, WUE_b was higher for rain–fed treatment in all the study years. Regulated deficit treatment had almost similar WUE_b values as that for unstressed treatment for crop season 2011–12. Despite underprediction made by Aquacrop for WUE_b, the model was able to predicit similar trend as observed for measured WUE_b (Fig. 4).

The regression equation between simulated and measured WUE_b shows higher underprediction made by the model specifically for regulated irrigation treatments resulting in higher Y–intercept of 6.9 kg/ha/mm. Model was able to simulate WUE_g comparatively better (R^2 = 0.70) than WUE_b (R^2 = 0.61), the difference between simulated and measured WUE_g ranged from 7 percent to –13 percent. Model generally underpredicted WUE_g except for rain–fed treatment of crop season 2009–10 in which 7 percent higher WUE_g was simulated. The regression equation between simulated and measured WUE_g shows better simulation made by the model for WUE_g compared to WUE_b.

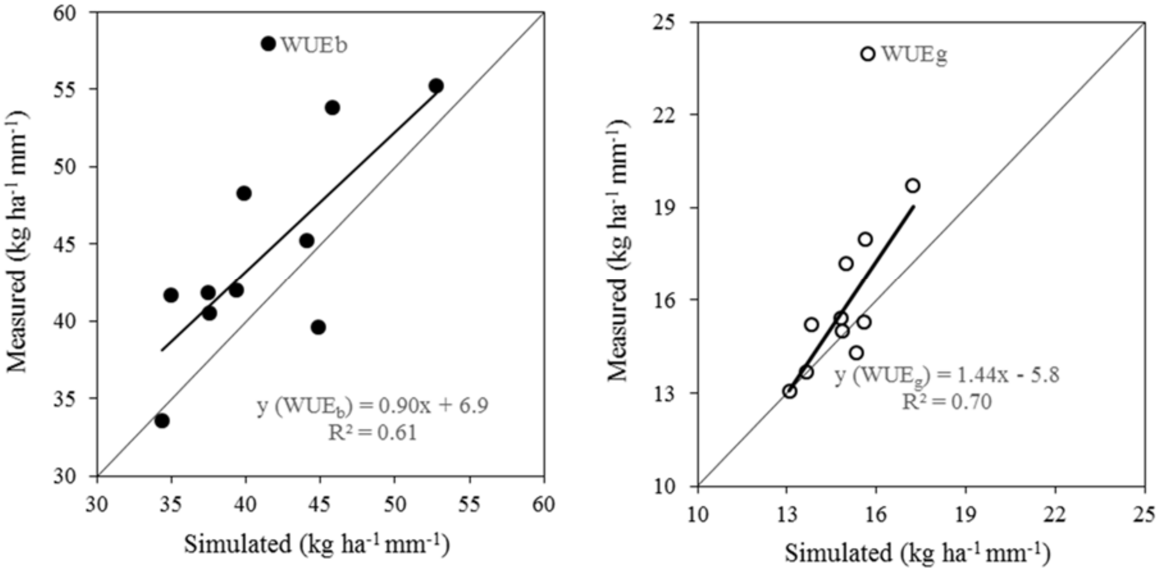

FIG.4. Simulated and measured wheat biomass and grain yield under different irrigation treatments.

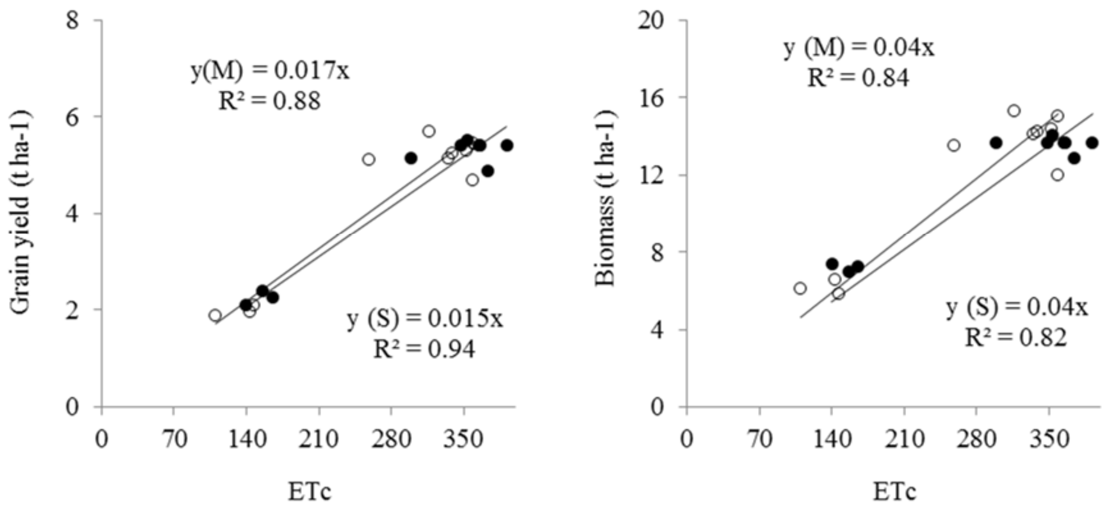

FIG.5. Relationship between simulated and measured aboveground biomass, grain yield with simulated and measured ETc for wheat.

Linear regression analysis (Fig. 5) of simulated and measured aboveground biomass with respective ETc values reveled significant relationship for simulated (R^2 = 0.82) and measured biomass (R^2 = 0.84). The slope of regression line (intercept set to zero) showed a simulated and measured increase of 0.04 t/ha in aboveground biomass for each additional unit of water consumed through ETc.

Regression analysis also indicated a good linear relationship between simulated and measured grain yield and respective ETc with values of R^2 = 0.94 for simulated grain yield and R^2 = 0.88 for measured grain yield. The relationship showed a simulated and measured yield increase of 15 and 17 kg, respectively, for a unit increase in ETc. The difference between measured and simulated slope was 11 percent which shows a reasonable simulation made by the model.

Figure 6 showed the separation of evapotranspiration estimated using AquaCrop in the present study. Soil evaporation was the main component of water loss during the early growth stage due to the low canopy cover; however, after the fourth week, crop transpiration increased and accounted for the majority of the total ET and remained higher during the vegetative growth and flowering stages. Although the Keeling plot isotopic method was carried out with extensive sampling of soil, air and plant moisture at different crop growth stages to validate the AquaCrop E and T patterns, the results were variable and further reassessment of the data is needed.

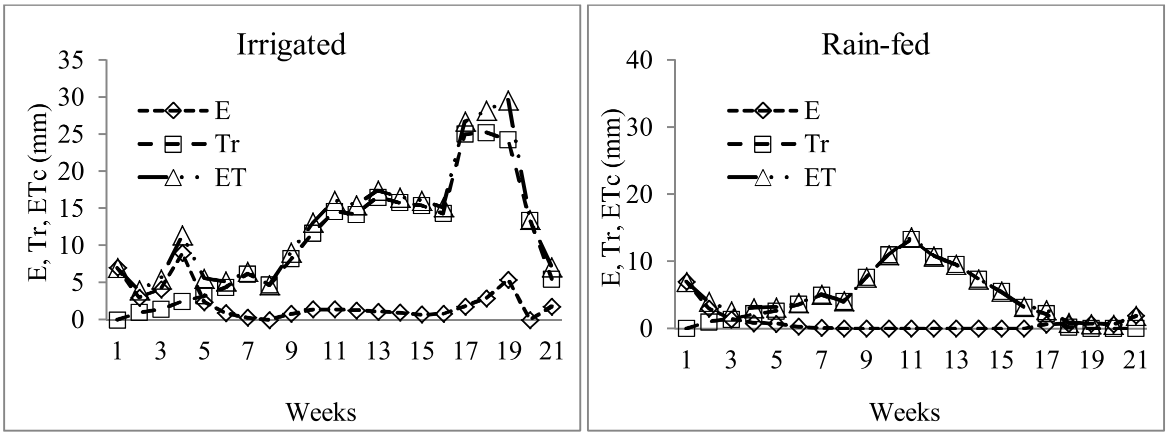

FIG.6. Pattern of wheat crop evapotranspiration and its components under rain–fed and irrigated conditions as determined by AquaCrop (2010–2011).

4. CONCLUSIONS

The present study showed that water use/transpiration efficiency of wheat could be improved by regulating plant–available water at crop stages more sensitive (tillering and grain formation) to water deficit, and by considering site–specific edaphic conditions. The water saved (up to 25 percent) by deficit irrigation at less sensitive crop stage(s) may allow irrigating additional crop area. The AquaCrop model can be a useful tool for assessing crop requirements and devising regulated deficit irrigation strategies to enhance water productivity under different scenarios in water scarce areas.

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