SESSION 5

MANAGING AGRICULTURAL WATER FOR CLIMATE CHANGE ADAPTATION

Enhancing the Contribution of Isotopic Techniques to the Expansion of Precision Irrigation

E. Fereres[1,*] and L.K. Heng[2]

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 therefore 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.

Key words: *precision agriculture, irrigation management, remote sensing, cosmic ray.*

INTRODUCTION

Nearly 70 percent of all freshwater abstractions worldwide are used in irrigation. As demands from other sectors increase and the options for developing new supplies tend to diminish, the need for saving water in irrigation is more imperative than ever before. Recent modernization efforts in the irrigation sector in many countries have shown that it is possible to reduce irrigation water use, albeit with increasing energy usage. Modernization focuses on minimizing conveyance losses by converting open channels to pipe networks, and on changing the method of irrigation from gravity to pressurized systems (sprinkler or drip). All these engineering changes increase the potential for highly efficient irrigation, but that potential can only be realized fully if the management of water is adequate.

Irrigation water management is a complex activity and one that often causes problems for growers in the context of improving irrigation efficiency. Adequate amounts applied at appropriate times are the ingredients for efficient irrigation. This is easier said than done, and most irrigators around the world use their qualitative skills to determine time and amount of irrigation rather than technical, quantitative procedures. However, in recent decades there have been substantial advances in irrigation management towards increasing the precision of water application.

Although the diversity of world agriculture is very significant, in all cases irrigated production can be related to one of three water resource situations. Firstly, where water is abundant and reliable, supplies are guaranteed each year. Here, the optimal amount of irrigation is dictated by energy costs and/or competition with other sectors, including the environment. Irrigation usually exceeds crop water requirements, excess water being applied as an insurance policy to avoid the risks associated with crop stress (water deficit), and hence substantial water savings are feasible. Secondly, there are situations where water supplies vary from being unconstrained to being restricted during periodic droughts. Adaptation in this context requires fine tuning of the irrigation equipment and its management. Here, there is scope for optimizing management and for substantial water savings in years of ample supply and by adopting better coping strategies in drought years. Finally, there is the situation of chronic water scarcity, mainly in the arid and semi-arid areas around the world, caused by a number of factors such irrigation over-expansion, competition from other sectors, notably the greater attention to environmental flows and unsustainable over-exploitation of groundwater resources. In this third situation, emphasis must be placed on optimizing use of the limited supplies by concentrating the available water on high-value crops and by using deficit irrigation (Fereres and Soriano, 2007) in a sustainable fashion. In all cases, science, engineering and management are the needed ingredients to achieve efficient use of water in agricultural systems.

PRECISION IRRIGATION

Recent droughts in many parts of the world and the threats of climate change with the uncertainties in future regional rainfall regimes, emphasize the need to have new irrigation strategies whereby increased precision in the use of water must play a central role in support of water conservation and environmental protection. Precision irrigation (PI) is defined here 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. There are two important prerequisites for successful application of PI: one is to know the crop water requirements (ET) with a certain degree of accuracy, and the other is to be able to monitor effectively the water status of the root zone. Much effort has been devoted to research for developing specific PI technologies based on new hardware (such as sensors) and/or new software (such as decision-support models), but its impact has been limited so far.

The first step for optimizing on-farm water management is using irrigation scheduling (IS) techniques to determine precisely the date and amount of irrigation (Fereres, 1996). A collection of techni-

1 IAS-CSIC and University of Cordoba, Spain
2 International Atomic Energy Agency, Wagramerstrasse 5, PO Box 100, 1400 Vienna, Austria
* E-mail address of corresponding author: ag1fecae@uco.es

L.K. Heng, K. Sakadevan, G. Dercon and M.L. Nguyen (eds), Proceedings — International Symposium on Managing Soils for Food Security and Climate Change Adaptation and Mitigation. Food and Agriculture Organization of the United Nations, Rome, 2014: 259–261

cal procedures and tools has been developed from analysis of the soil–plant–atmosphere continuum allowing the depth and frequency of irrigation applications to be forecast. The most robust technique for IS is the soil water budget. Here, irrigation timing is computed by adding the crop ET losses minus effective rainfall until a soil water level termed the allowable depletion is reached. Nowadays, agrometeorological weather station networks provide the information needed for calculating reference evapotranspiration (ETo) from meteorological variables, while crop coefficient (Kc) values for the major water demanding crops have also been determined (FAO, 1998). Computer programs have been developed for calculating the water balance of fields, and irrigation scheduling services have been developed, mostly by public agencies but also by private consultants. The soil water budget method, despite being widely used, has some uncertainties. These include assumptions about 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. Also, there is uncertainty about the optimum frequency of irrigation, which depends upon several field and irrigation system design characteristics and which, in turn, is very difficult to take into account in simple models. Nevertheless, the frequency of irrigation is a crucial aspect of irrigation scheduling, determining largely the overall on-farm irrigation efficiency.

Soil water status determinations can be carried out to visualize the effects of the irrigation regime on soil water availability. There is now a new generation of soil water sensors which track soil water status continuously rather than providing intermittent measurements as offered by the traditional instruments such as the tensiometer (Leib *et al.*, 2003). 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 (IAEA, 2008). However, obtaining a representative estimate of the soil water content of a whole field is a difficult task when using point sensors, due to the very large soil water variability resulting from variations in soil properties and the fact that under localized irrigation, the soil surface is not uniformly wet. The strong spatial heterogeneity of soil water status even in what are considered uniform soils, combined with the variations in the distribution of irrigation water applications and the uncertainties of rooting depth and densities, all contribute to create a heterogeneous environment that farmers have to manage as accurately as possible. In developed countries, this problem has become more pronounced in the last decades due to the increased size of management units, in an attempt to reduce production costs by managing uniformly large field units. The complexities involved in dealing with the variability problem are such that, until very recently, the common solution chosen by irrigators was to apply water in excess so that the risk of inducing water deficits in some parts of the field is minimized. Because of the difficulties that farmers and technicians have had in characterizing the variability, significant uncertainty is introduced and often irrigation management decisions may have substantial errors.

To advance solutions for coping with the variability problem, i.e. to implement PI under field conditions, what is needed is to be able to characterize the variation across a field, and also to have the option of applying variable amounts of water within that field. The objective would then be 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. The technologies for variable water application are already available in self-propelled sprinkler systems and can lead to significant water conservation (Sadler *et al.*, 2005). Significant efforts in the engineering of irrigation systems have been undertaken recently to offer the flexibility of applying spatially variable amounts of water (and agrochemicals) for the different pressurized methods, including micro-irrigation (Evans and Sadler, 2007). These new PI capabilities should enable growers to increase productivity and minimize the negative environmental impacts of irrigation.

While the engineering solutions for PI are underway, there is still the need to both characterize and monitor the variability as well as to interpret the causes of variations in crop growth and development. The characterization of irrigation performance through remote sensing (Santos *et al.*, 2010) is a promising area, as it enables performance to be evaluated quickly and inexpensively; it can also identify areas in need of improvement. The use of remote sensing techniques has progressed substantially in recent years through the development of capabilities for detecting a number of vegetation properties with very high resolution (Zarco-Tejada *et al.*, 2009). High-resolution images cannot be acquired from current satellites, and a number of initiatives have been launched recently to obtain these from aerial vehicles flying closer to the ground

ISOTOPIC TECHNIQUES FOR PRECISION IRRIGATION MANAGEMENT

Effective irrigation management requires accurate knowledge of crop water requirements (ETc) and knowledge of the average water status of the crop–soil system and its variation among and within management units. Isotopic techniques (using oxygen-18 and deuterium isotopes) that quantify the separation of evaporation (E) and transpiration (T) are important research tools to determine the relative magnitudes of E and T in different situations (Williams *et al.*, 2004; Heng *et al.*, 2013, these proceedings). Evaporation rates vary widely from 50 percent to 10 percent of ETc or less under conditions of complete radiation interception by the crop canopy (Villalobos and Fereres, 1990). Isotopic techniques based on oxygen-18 can be used to compute the magnitude of E in many situations, e.g. where subsurface drip irrigation is economically viable and can lead to water savings relative to other irrigation methods.

ASSESSING SOIL WATER OVER LARGE AREAS: THE COSMIC-RAY SOIL MOISTURE OBSERVING SYSTEM (COSMOS)

Making point observations of soil water or plant water status to assess the "average" water status of large areas and thereby reduce the variability problem is not feasible. The cosmic-ray neutron probe (Zreda *et al.*, 2008; Shuttleworth *et al.*, 2010) is a new instrument that can provide measurements of "area-average" soil water content over a circle of about 700 m diameter and over depths varying between 15 and 70 cm (Zreda *et al.*, 2008, 2012; Franz *et al.*, 2012). Monitoring areas at these scales allows the integration of variations caused by differences in soil–crop properties and in the distribution of irrigation water. A sequence of observations over time also permits the computation of the components of the field water balance if the appropriate inputs and outputs are recorded.

To advance solutions for coping with the variability problem one needs, firstly, to characterize the variation across a field and, if unmanageable as a single unit, then to be able to apply variable amounts of water within that field. The common decision to irrigate based on averaging field indicators and integration of some farm constraints should give way to the idea of using sub-field areas to decide and then integrate field and farm constraints. Such sub-fields should have "uniform" characteristics and potentialities, and should be watered differentially from others, as is already practised for seeding, fertilizing or in pesticide applications in precision farming.

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 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

REFERENCES

Evans, R.G. & Sadler, E.J. 2007. *New technologies to improve crop water use efficiencies*. No. S164. Carrollton, TX, Lawrence Media Group.

FAO. 1998. *Crop evapotranspiration — Guidelines for computing crop water requirements,* by R.G. Allen, L.S. Pereira, D. Raes & M. Smith. FAO Irrigation and Drainage Paper, No. 56. Rome.

Fereres E. 1996. Irrigation scheduling and its impact on the 21st century. Proceedings of the International Conference on Evapotranspiration and Irrigation Scheduling, pp. 547–553**.** San Antonio, TX. St Joseph, MI, American Society of Agricultural Engineers.

Fereres, E. & Soriano, M.A. 2007. Deficit irrigation for reducing agricultural water use. *J. Exp. Bot.,* 58: 145–159.

Franz, T.E., Zreda, M., Rosolem, R. & Ferre, T.P.A. 2012. Field validation of a cosmic-ray neutron sensor using a distributed sensor network. *Vadose Zone J.,* 11, p. vzj2012.0046.

Heng, L.K., Hsiao, T.C., Williams, D., Fereres, E., Cepuder, P., Denmead, T., Amenzou, N., Dhan, N., Duong, H., Kale, S., Li, B.G., Mahmood, K., Mei, X.R., Phiri, E., Zingore, S. & Nguyen, M.L. 2013. Managing irrigation water to enhance crop productivity under water-limiting conditions: A role for isotopic techniques. (*These Proceedings*).

Hsiao, T.C., Heng, L.K., Guo, B., Gong, D., Li, B.G., Williams, D.G. & Kale, S. 2013. Field comparison of methods for measuring evapotranspiration and soil evaporation, including a stable isotope method. (*These Proceedings*).

IAEA. 2008. *Field estimation of soil water content: A practical guide to methods, instrumentation and* sensor technology. Training Course Series No. 30. (available at: http://www-pub.iaea.org/MTCD/publications/PDF/TCS-30_web.pdf).

Leib, B.G., Jay, J., Matthews, D. & Gary, R. 2003. Field evaluation and performance comparison of soil moisture sensors. *J. Soil Sci.,* 168: 396–408.

Sadler, E.J., Evans, R.G., Stone, K.C. & Camp, C.R. 2005. Opportunities for conservation with precision irrigation. *J. Soil Water Conserve*., 60: 371–379.

Santos, C., Ignacio, J., Lorite, M., Tasumi, R., Allen, G. & Fereres, E. 2010. Performance assessment of an irrigation scheme using indicators determined with remote sensing techniques. *Irrig. Sci.,* 28: 461–477.

Shuttleworth, W.J., Zreda, M., Zeng, X., Zweck, C. & Ferre, P.A. 2010. The COsmic-ray Soil Moisture Observing System (COSMOS): *A non-invasive, intermediate scale soil moisture measurement network*. Proceedings British Hydrological Society's Third International Symposium: "Role of Hydrology in Managing Consequences of a Changing Global Environment", Newcastle University, 19–23 July 2010, ISBN:1903741173.

Villalobos F.J. & Fereres, E. 1990. Evaporation measurements beneath corn, cotton and sunflower canopies. *Agron. J.*, 82: 1153–1159.

Williams, D. G., Cable, W., Hultine, K., Hoedjes, J.C.B., Yepez, E.A., Simonneaux, V., Er-Raki, S., Boulet, G., de Bruin, H.A.R., Chehbouni, A., Hartogensis, O.K. & Timouk, F. 2004. Evapotranspiration components determined by stable isotope, sap flow and eddy covariance techniques. *Agric. For. Meteorol.,* 125: 241–258.

Zarco-Tejada, P.J., Berni, J.A.J., Suárez, L., Sepulcre-Cantó, G., Morales, F. & Miller, J.R. 2009. Imaging chlorophyll fluorescence from an airborne narrow-band multispectral camera for vegetation stress detection. *Rem. Sens. Environ.,* 113: 1262–1275.

Zreda, M., Desilets, D., Ferre, T.P.A. & Scott, R.L. 2008: Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons. *Geophys. Res. Lett.,* 35: L21402, doi:10.1029/2008GL035655.

Zreda, M., Shuttleworth, W.J., Xeng, X., Zweck, C., Desilets, D., Franz, T.E., Rosolem, R. & Ferre. P.A. 2012. COSMOS: The COsmic-ray Soil Moisture Observing System. *Hydrol. & Earth Syst. Sci.,* 16: 4079–4099.

Partitioning Wheat Transpiration and Soil Evaporation with Eddy Covariance, Stable Isotope and Micro-Lysimeter Methods in the North China Plain

D. Gong[1, 2], X. Mei[1,*], J.Shi[3], W. Hao[1] and L. Heng[4]

ABSTRACT

The dynamics of water vapour delta oxygen-18 ($\delta^{18}O$) at five different heights were monitored continuously in a wheat field by a stable water vapour isotope analysis system. Combined with a Keeling plot curve this was used to partition evapotranspiration (ET) into its components of evaporation (E) and transpiration (T) which were compared with estimations using the eddy covariance system and a micro-lysimeter (i.e. EC-MLS method). There was significant agreement between the ratio E:ET estimated by the stable isotopic and conventional methods ($R^2 = 0.8468$, n = 27), indicating that the combination of the isotopic Keeling plot method with *in situ* continuous measurements of stable isotope composition of water vapour accurately partitioned ET in the wheat field. The stable isotope composition of atmospheric water vapour (δv) in the wheat field decreased significantly after irrigation events and was linearly related to vapour pressure deficit (VPD) and solar radiation (Rn) with correlation coefficients (R) of 0.696 (n = 1250, $\alpha < 0.001$) and 0.704 (n = 1250, $\alpha < 0.001$), respectively. The stable isotope composition of water vapour arising from soil evaporation (δ_E) also had significant isotopic fractionation effects which were alleviated by low soil water content and VPD.

Key words: *evapotranspiration, stable isotope, eddy covariance, soil evaporation, Keeling plot, partition.*

INTRODUCTION

At farmland scale, evapotranspiration (ET) can be measured easily by conventional methods such as the Bowen ratio (Angus and Watts, 1984), eddy covariance (Wilson *et al*., 2001), the gradient system and weighting macro-lysimeters (Liu, Zhang and Zhang, 2002). However, it is difficult to distinguish its components: plant transpiration (T) and soil evaporation (E), which are controlled by different mechanisms and to different degrees by biotic and abiotic factors (Raz-Yaseef *et al.*, 2012). Soil evaporation is equal to about 30 percent of ET during the whole plant development period under the common irrigation pattern used in the North China Plain (Liu, Zhang and Zhang, 2002). Partitioning ET accurately into these two components can enhance understanding of water loss processes at the interfaces of the soil–plant–atmosphere continuum (SPAC), which helps us to explore solutions to improve crop water productivity.

Conventional methodologies for separating ET include (i) a combination of soil lysimeters for E and sap flow sensors/chambers for plant T (Gong *et al*., 2007); (ii) an eddy covariance system/Bowen ratio system/gradient system/weighting macro-lysimeter for ET and soil lysimeters for E (Liu, Zhang and You, 1998); (iii) an eddy covariance system/Bowen ratio system/gradient system/weighting macro-lysimeter for ET and sap flow sensors/chamber system for plant T; and (iv) theoretical methods such as the Shuttleworth-Wallace model (Hu *et al.*, 2009), the dual crop coefficients method (Er-Raki *et al*., 2010) and time series analysis (Scanlon and Kustas, 2010). The first approach suffers from poor spatial representation (Wang *et al*., 2010), the second and third methods must solve the problem of transforming scale from point to farmland, and the last ones are confronted with the difficulty of parameter uncertainties.

Incorporating measurements of water isotopic concentration in soil, plant and air vapour can address the limitations of these conventional methods. Significantly, if the isotopic signal of T reaches steady state, the isotopic enrichment of leaf water can be omitted and the isotopic concentration of the plant T vapour equates with that of the local soil water absorbed by roots. Nevertheless, the lighter H_2 oxygen-16 ($H_2{}^{16}O$) molecules, which have a higher vapour pressure and binary diffusivity compared with the heavier isotopologues (HDO or $H_2{}^{18}O$), evaporate more readily from soil, leaving the soil water pools more enriched in delta (δ) ^{18}O and delta deuterium (δD). This results in a significant difference between the isotopic concentration of water vapour from T and E. The different isotopic signals of T and E can provide the basis to separate the total water flux at farmland scales (Wang and Yakir, 2000).

Since Yakir and Wang's (1996) pioneering work on stable isotope methods for partitioning ET, the cold-trap technique has been used for collecting air moisture and stable isotope analysis. However, the traditional cold-trap method is time consuming and labour intensive, and has limited applications to short period (several days),

1 State Engineering Laboratory of Efficient Water Use of Crops and Disaster Prevention and Loss Reduction, Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agriculture Science, Beijing 100081, P.R. China
2 State Key Laboratory of Hydro-science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, P. R. China
3 Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas, Ministry of Education, Northwest A & F University, Yangling 712100, P. R. China
4 Soil and Water Management and Crop Nutrition Section, Joint FAO/IAEA Division, International Atomic Energy Agency, A-1400 Vienna, Austria
* E-mail address of corresponding author: meixr@ieda.org.cn

L.K. Heng, K. Sakadevan, G. Dercon and M.L. Nguyen (eds), Proceedings — International Symposium on Managing Soils for Food Security and Climate Change Adaptation and Mitigation. Food and Agriculture Organization of the United Nations, Rome, 2014: 263–268

small-scale (chamber scale) studies with low time precision (daily). At present, real-time and continuous measurements of $\delta^{18}O$ and δD in air vapour and liquid water by tunable diode laser absorption spectroscopy provide an opportunity to perform *in situ* and continuous ET partitioning on a diurnal timescale (Zhang *et al*., 2010).

The main objective of this study was to develop and evaluate an isotopic method for separating plant T and soil E using *in situ* continual measurements from a laser-based isotope system and the Keeling plot approach, and to verify this method using measurements from an eddy covariance system and micro-lysimeters.

MATERIALS AND METHODS

Experimental site and plant materials

The experiment was conducted on a winter wheat field at the National Precision Agriculture Station, Changping, Beijing, China (40°11′ N, 116°26′ E, 43 m a lt.), (Figure 1). The climate is temperate (average temperature 12°C and mean annual rainfall 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 fluvo-aquic with a loam texture and an average bulk density of 1.42 g/cm^3. At the root zone (0–100 cm), the volumetric soil water content at field capacity and wilting point were 33 percent and 16 percent, respectively. The field experimental plot area was about 4.5 ha (length 150 m, width 300 m), which fulfills the installation requirements of the eddy covariance system. The wheat was sown in October 2010 at a density of 600 000 seeds/ha. During the period of observation from April–June 2011, the total precipitation was only about 60 mm, and the wheat was irrigated two times using a sprinkler system. The amounts of irrigation water were about 75 mm and 45 mm. Rainfall and the quantities of irrigation and soil water content (at 0–200 cm depth) at the study site are shown in Figure 2. The two large increments in soil water content were due to the irrigation events.

Measurements of evapotranspiration and soil evaporation at farmland scale

An eddy covariance (EC) system was installed in the centre of the plot 1.5 m above the wheat canopy to monitor ET. Fluxes of latent (LE) and sensible heat (H) were monitored using respectively a LI-7500 H_2O/CO_2 analyzer and a CAST3 three-dimensional sonic anemometer. Net radiation (Rn) over the field was measured at a height of 4.2 m by a four-way net radiometer (CNR1, Kipp & Zonen Inc., Delftechpark, The Netherlands). Soil heat flux was measured using heat flux plates with a constant thermal conductivity (HFT3, Campbell Scientific Inc., Logan, UT, USA).The accuracy of the EC system measurements was evaluated based on the energy balance principle.

Soil E was measured with micro-lysimeters (Boast and Robertson, 1982) during dry periods. Considering there was uneven coverage of the winter wheat foliage which gives rise to heterogeneity in the incoming radiation and rainfall at the soil surface, seven micro-lysimeters were installed randomly in the windy upstream direction of the eddy covariance system to measure daily soil evaporation. These had an internal diameter of 7.0 cm and a depth of 17.5 cm. The bottom of each micro-lysimeter was capped with a steel plate that did not permit free drainage of water. In this experiment, soil in the micro-lysimeters was replaced every two or three days to avoid any divergence from the surrounding soil due to cessation of root extraction and water exchange with subsoil.

Measurements of stable isotope ratios of vapour, soil and plant water

Air δD, $\delta^{18}O$ isotope signatures and vapour concentrations at different heights (5, 50, 80, 120 and 160 cm) were monitored using a cavity ring down spectroscopy stable isotopic water vapour analysis system (Picarro Inc.). Soil samples at different depths (2, 5, 10 and 15 cm) on three sites and five plant stem samples were collected at intervals of 2–3 days to measure isotopic values of water using an elemental analyzer.

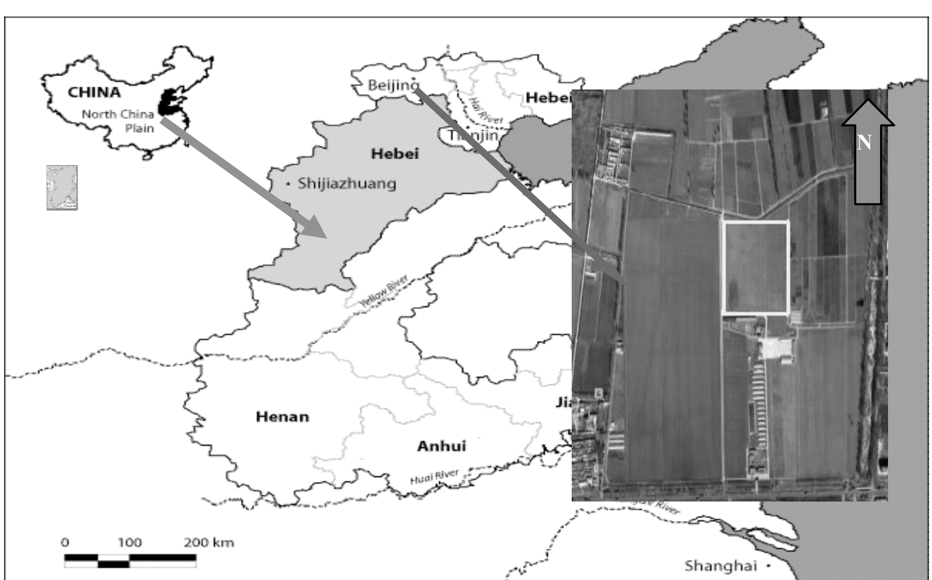


FIGURE 1. Schematic diagram of the experimental station and experimental plot.

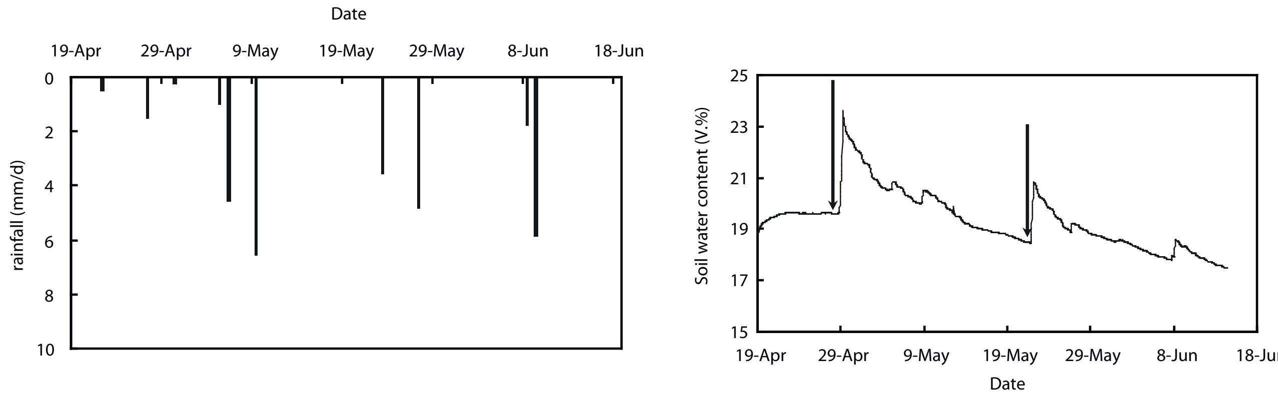


FIGURE 2. Daily rainfall (left), irrigation (right, arrows downward), and soil water dynamics at Changping (April–June 2011).

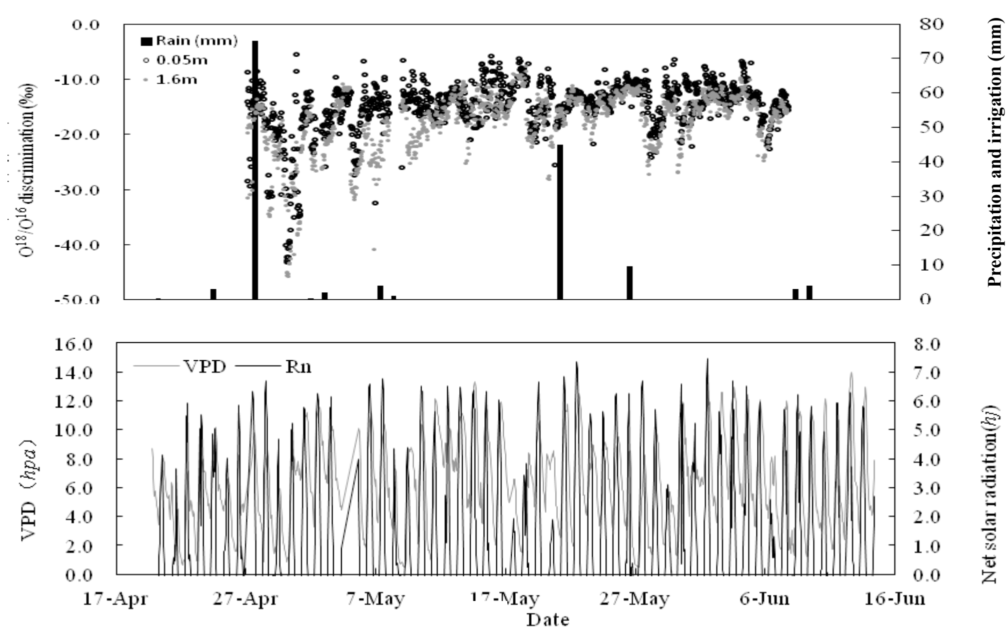


Figure 3. The dynamics of vapour stable composition ($\delta^{18}O$) during the experimental period.

Canopy cover (C_c) measurements

Canopy cover was measured using a LI-191 Line Quantum Sensor (LI-COR Inc., Lincoln, NB, USA). Rather than using multiple detectors arranged linearly over its 1 m length, the LI-191 uses a 1 m-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 (C_c) was calculated using the equation:

$$C_c = 1 - (PPFD_b/PPFD_a) \tag{1}$$

Meteorological measurements

Meteorological data were measured in a standard automatic weather station nearby the experiment plots. Variables measured included global radiation, air temperature, air humidity, rainfall, and wind speed at 2 m above ground.

Theory description

The general approach for partitioning *ET* into its components is based on simple isotopic mass balance and that the contribution to atmospheric moisture from the farmland surface arises from soil *E* and plant *T*:

$$ET = E + T \tag{2}$$

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

$$\delta_{ET} = \delta_E + \delta_T \tag{3}$$

where δ is the isotopic composition and subscripts ET, E, and T denote respectively evapotranspiration, evaporation and transpiration.

Assuming that $F_S = E/ET$, and substituting $T = ET - E$ from Equation (2) into Equation (3) and rearranging, Fs is obtained as:

$$F_S = \frac{\delta_{ET} - \delta_T}{\delta_E - \delta_T} \tag{4}$$

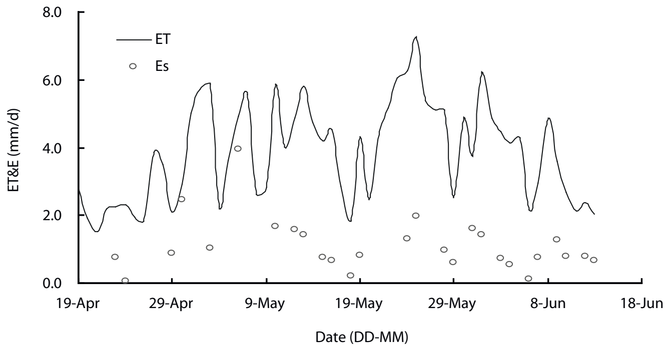


FIGURE 4. Dynamics of evapotranspiration (ET) and soil evaporation (E) estimated by eddy covariance and micro-lysimeters during the experimental period.

where δ_{ET} is estimated using the Keeling mixing model (Keeling, 1961); δ_E is estimated using the Graig and Gordon (1965) model, and δ_T is estimated from the isotopic values of stem water.

RESULTS AND DISCUSSION

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

Figure 3 shows that the $\delta^{18}O$ composition of air vapour in the winter wheat field changed with rainfall and irrigation (R and I), vapour pressure deficit (VPD) and net solar radiation (R_n) at two heights (0.05 m and 1.60 m) from April to June in 2011. The $\delta^{18}O$ of the lower layer (0.05 m) was greater than that of higher layer (1.60 m) because the $\delta^{18}O$ composition of the vapour derived from soil evaporation and the atmospheric background are very different. The difference between the low and high layers was about 0~10.0‰, and was related to the weather conditions. These were similar to the isotopic composition distribution of vapour in a forest (Lee, Kim and Smith, 2007). The stable isotope composition of vapour $\delta^{18}O$ was about –45.00‰ ~ –5.00‰ during the observation period. In the rainfall and irrigation periods the average daily stable isotope values of vapour $\delta^{18}O$ decreased rapidly, and then increased gradually to the maximum because of the isotopic fractionation effects of soil water evaporation. This is consistent with the findings of Yuan *et al*. (2010). Statistical analyses of the results showed that the $\delta^{18}O$ composition of air vapour at the two heights correlated significantly with VPD and R_n with average correlation coefficients of about 0.696 ($n = 1250$, $\alpha < 0.001$) and 0.704 ($n = 1250$, $\alpha < 0.001$).

The ratio of soil evaporation to evapotranspiration estimated by eddy covariance and micro-lysimeters

Results for evapotranspiration (ET) and soil E estimated by the eddy covariance system and using micro-lysimeters are shown in Figure 4. Evapotranspiration increased during the initial stages of wheat development, stabilized in the middle of the growth period and decreased during the late growth period. During the whole observation period the maximum and minimum rates of ET were 7.2 mm/day (May 25) and 1.5 mm/day (April 21), respectively, while the corresponding values for E were 2.4 mm/day and 0.4 mm/day.

The ratio of plant transpiration to evapotranspiration estimated by the isotopic method and its comparison with the EC-MLS method

Gradients in atmospheric moisture content and isotopic composition through the profile of the canopy boundary layer were observed during the experimental period. Linear regressions were fitted to mid-day (11.00–15.00 h) data to estimate δ_{ET}, the isotopic composition of the ET flux (Figure 5). There was a significant relationship between inversion of atmospheric moisture content and isotopic composition of water vapour, suggesting that the Keeling plot method for estimating the isotopic composition of the ET flux from continuous

Table 1. Parameters of the Craig-Gordon model and estimates of evaporation flux δ_E on selected days

Date	$\alpha_{L\text{-}V}$	$\varepsilon_{L\text{-}V}$	h	Δξ(‰)	δ_V(‰)	δ_S(‰)	δ_E(‰)
4–23	0.9800	19.957	0.26	21.105	–27.48	–5.32	–46.83
4–30	0.9883	11.702	0.51	14.020	–18.54	–10.05	–48.16
5–6	0.9867	13.274	0.47	15.132	–12.96	–9.33	–47.39
5–9	0.9882	11.798	0.43	16.160	–15.75	–10.11	–43.51
5–18	0.9932	6.753	0.67	9.536	–11.73	–5.47	–53.02
5–22	0.9914	8.565	0.61	11.220	–15.59	–12.42	–42.71
5–28	0.9924	7.571	0.67	9.521	–11.48	–9.70	–37.45
5–31	0.9948	5.219	0.65	9.990	–18.65	–10.63	–48.12
6–3	0.9956	4.433	0.35	18.519	–15.68	–6.63	–33.56
6–6	0.9964	3.566	0.71	8.286	–11.04	–9.05	–36.58
6–9	0.9967	3.298	0.78	6.264	–11.05	–5.92	–55.82
6–12	0.9974	2.631	0.48	14.687	–18.47	–10.87	–29.89

Note: $\alpha_{v\text{-}l}$ is the equilibrium fractionation factor for liquid–vapour exchange of H_2O; $\varepsilon_{v\text{-}l}$ is another form of $\alpha_{v\text{-}l}$; h is the soil relative humidity; Δξ is kinetic fractionation factor; δ_v is the vapour water $\delta^{18}O$ isotopic value measured by a stable water vapour isotope analysis system (Picarro Inc.); δ_s is the average isotopic values of water at the soil surface; δ_E is fitting value of water vapour from soil evaporation.

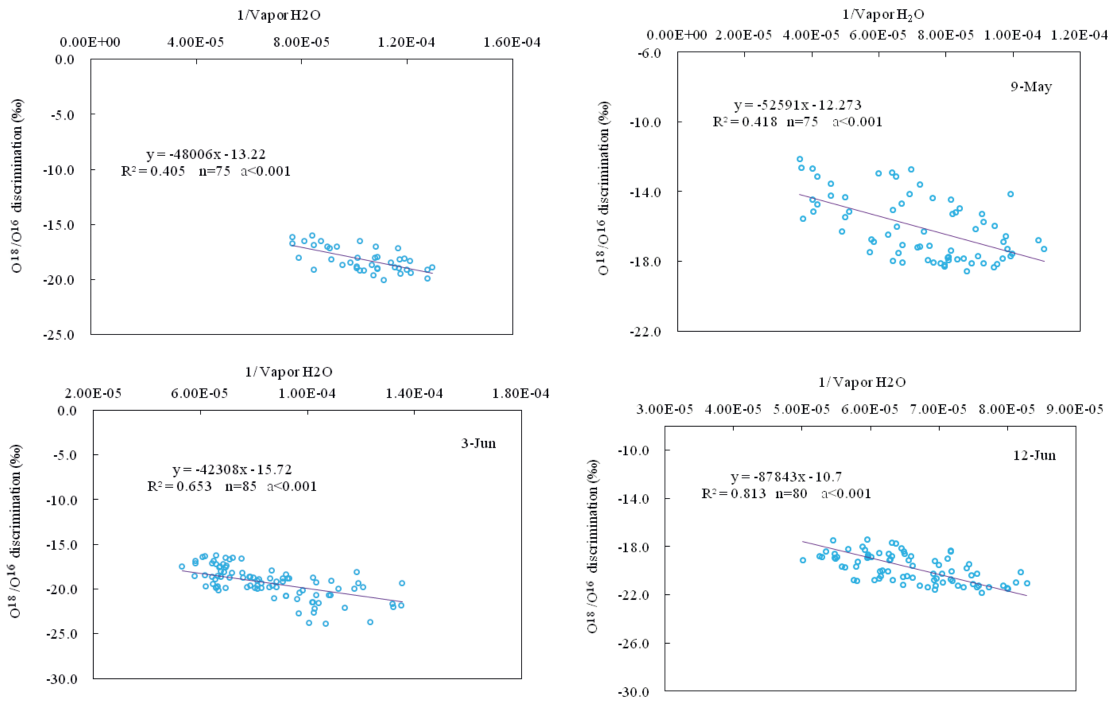


Figure 5. Daytime Keeling plots of water vapour monitored for $\delta^{18}O$ by a cavity ring-down spectroscopy (Picarro Inc.) at different heights above the ground on selected days.

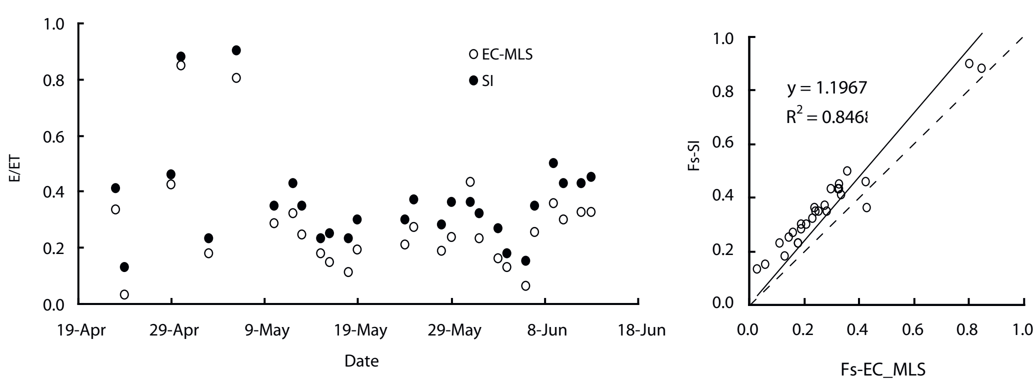


FIGURE 6. Seasonal changes in the ratios of E to ET (F_S) estimated by conventional (o) and isotopic (•) methods (left), and their interrelationship (right).

measurements using the water vapour stable isotopic analysis system was feasible in the wheat fields of the North China Plain.

The stable isotope composition of soil evaporation (δ_E) in the wheat field and various other parameters were estimated from the isotope fractionation coefficients and the Craig-Gordon model for stable isotope composition of the soil evaporation (Table 1). The values of δ_E of soil evaporation were mostly about -30 ‰ ~−50 ‰, which is smaller than δ_S of the soil water, indicating that there was obvious isotope fractionation during the soil evaporation process. These results are consistent with the findings of Yuan *et al.* (2010).

The stable isotope compositions of wheat field evapotranspiration (δ_{ET}), soil evaporation (δ_E) and crop stems (δ_T), were used to calculate E/ET according to Equation (4), and the results compared with values estimated by the conventional method (Figure 6, left). The E/ET ratios during the early and late growing seasons were higher than that in the mid growing season because of the smaller canopy cover in the early and late seasons. The E/ET ratios estimated by the stable isotopic method were almost 20 percent higher than by combining the eddy covariance and mini-lysimeter methods. There was significant agreement between the E/ET ratio estimates from the stable isotopic and conventional methods (R^2 = 0.8468, n = 27) (Figure 6, right). These results are consistent with the findings of Zhang (2009).

The relationship between E:ET and canopy cover (C_c)

The ratio (E/ET) is controlled by canopy cover, the wetting area of the soil surface layer and weather conditions. Figure 7 shows the curve fitted between E/ET estimates by the conventional method and from crop canopy cover (C_c). There was a significant negative linear relationship between average E/ET and C_c (correlation coefficients, R^2 = 0.936, n = 7), indicating that E/ET decreased with increasing C_c because the amount of solar radiation reaching the soil surface decreased as the crop leaf area increased.

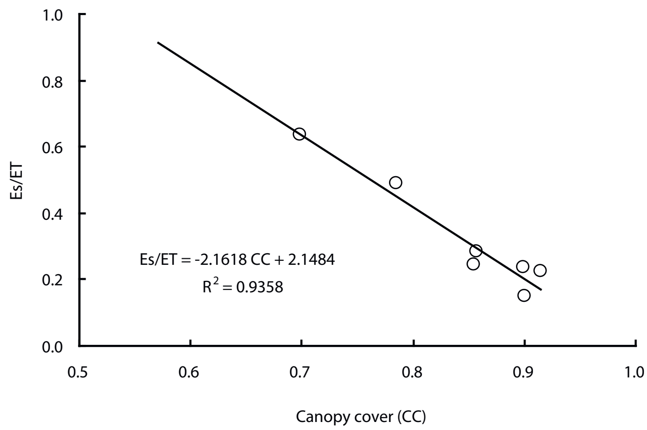


FIGURE 7. Relationship between E/ET estimated by the eddy covariance micro-lysimeter method and from canopy cover (C_c).

CONCLUSIONS

This study has shown that E/ET ratios esti 1mated by an on-line stable isotopic air vapour analysis system using a cavity ring-down spectroscopy were comparable with those obtained by the conventional method, demonstrating that the partition of ET into E and T components by the isotopic method is feasible and reliable in the North Plain of China. The isotopic method gives rapid and reliable results, but whether it provides the precision required by researchers needs further investigation.

ACKNOWLEDGMENTS

The authors 1are grateful for the support provided by the FAO/IAEA Coordinated Research Project 14523 and by the Chinese National Natural Science Fund, Project nos. 51179194, 30871447 and 50709040).

REFERENCES

Angus, D.E. & Watts, P.J. 1984. Evapotranspiration – how good is the Bowen ratio method? *Agric. Water Manage.,* 8: 133–150.

Boast, C.W. & Robertson, T.M. 1982. A "micro-lysimeter" method for determining evaporation from bare soil: description and laboratory evaluation. *Soil Sci. Soc. Am. J.,* 46: 689–696.

Craig, H. & Gordon, L.I. 1965. Deuterium and oxygen-18 variations in the ocean and the marine atmosphere, *In* E. Tongiorgi, ed. *Stable isotopes in oceanographic studies and paleotemperatures,* pp. 9–130. Pisa, Italy, Laboratory of Geology and Nuclear Science.

Er-Raki, S., Chehbouni, A., Boulet, G. & Williams, D.G. 2010. Using the dual approach of FAO-56 for partitioning ET into soil and plant components for olive orchards in a semi-arid region. *Agric. Water Manage.,* 97: 1769–1778.

Gong, D.Z., Kang, S.Z., Zhang, L. & Yao, L.M. 2007. Estimation of evapotranspiration and its components from an apple orchard in northwest China using sap flow and water balance methods. *Hydrol. Process.,* 21: 931–938.

Hu, Z.M., Yu, G.R., Zhou, Y.L., Sun, X.M., Li, Y.N., Shi, P.L., Wang, Y.F., Song, X., Zheng, Z.M., Zhang, L. & Li, S.G. 2009. Partitioning of evapotranspiration and its controls in four grassland ecosystems: Application of a two-source model. *Agric. Forest Meteorol.,* 149: 1410–1420.

Keeling, C.D. 1961. The concentration and isotopic abundances of carbon dioxide in rural and marine air. *Geochim. Cosmochim. Acta*, 24: 277–298.

Lee, X., Kim, K. & Smith R. 2007. Temporal variations of the isotopic signal of the whole-canopy transpiration in a temperate forest. *Global Biogeochem. Cycle*, 21: 1–12.

Liu C.M., Zhang X.Y. & You M.Z. 1998. Determination of daily evaporation and evapotranspiration of winter wheat field by large-scale weighing lysimeter and micro-lysimeter. *J. Hydraul. Engin.,* 10: 36–39 (in Chinese with English abstract).

Liu, C.M., Zhang X.Y. & Zhang Y.Q. 2002. Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter. *Agric. & Forest Meteorol.,* 111: 109–120.

Raz-Yaseef, N., Yakir, D., Schiller, G. & Cohen, S. 2012. Dynamics of evapotranspiration partitioning in a semi-arid forest as affected by temporal rainfall patterns. *Agric. & Forest Meteorol.,* 157: 77–85.

Scanlon, T.M. & Kustas, W.P. 2010. Partitioning carbon dioxide and water vapor fluxes using correlation analysis. *Agric. & Forest Meteorol.*, 150: 89–99.

Wang, L.X, Caylor, K.K., Villegas, J.C., Barron Gafford, G.A., Breshears, D.D. & Huxman, T.E. 2010. Partitioning evapotranspiration across gradients of woody plant cover: Assessment of a stable isotope technique. *Geophys. Res. Lett.,* 37 L09401: 1–7.

Wang, X.F. & Yakir, D. 2000. Using stable isotopes in evapotranspiration studies. *Hydrol. Process.*, 14: 1407–1421.

Wilson, K.B., Hanson P.J., Mulholland P., Baldocchi D.D. & Wullschleger S. 2001. A comparison of methods for determining forest evapotranspiration and its components: sap flow, soil water budget, eddy covariance and catchment water balance. *Agric. & Forest Meteorol.*, 106, 153–168.

Yankir D. & Wang, X.F 1996. Fluxes of CO_2 and water between terrestrial vegetation and atmosphere estimated from isotope measurements. *Nature,* 380: 515–517.

Yuan G.F., Zhang N., Sun X.M., Wen X.F. & Zhang S.C. 2010. Partitioning wheat field evapotranspiration using Keeling plot method and continuous atmospheric vapor $\delta^{18}O$ data. *Chin. J. Plant Ecol.*, 34: 170–178. (in Chinese with English abstract).

Zhang N. 2009. V*ariation of* $\delta H_2{}^{18}O$ *in wheat SPAC system and ET partitioning.* Beijing, Graduate School of Chinese Academy of Sciences. (MA thesis; in Chinese with English abstract).

Zhang S.C., Wen X.F., Wang J.L., Yu G.R. & Sun X.M. 2010. The use of stable isotopes to partition evapotranspiration fluxes into evaporation and transpiration. *Acta Ecol. Sinica*, 30: 201–209.

Isotopic and Conventional Techniques to Improve the Irrigation Practice in Order to Enhance Agriculture Production under Water Limiting Conditions in Morocco

N. Amenzou[1,*], H. Marah[1], F. Raibi[1], J. Ezzahar[1], S. Khabba[2], J. Lionel[3] and M. Ismaili[4]

ABSTRACT

Sound and efficient irrigation practices are important for achieving sustainable management of water resources for agriculture in arid and semi-arid regions. An experiment was conducted to monitor seasonal water consumption of citrus plants irrigated by a drip irrigation system at the Agafay station in the middle of Morocco. For this purpose, an eddy-covariance (EC) system, a meteorological station and a fluxmeter were employed, as well as measurements of soil moisture and temperature which were made available continuously during the experimental period. The oxygen-18 stable isotope was used to partition evapotranspiration (ET) fluxes, i.e. a Keeling Plot with data from five layers inside a mandarin orchard being generated to assess ecosystem isotopic flux. The results suggest that loss by percolation constituted about 38 percent of the cumulative amounts of irrigation and rainfall. Partitioning of ET showed that transpiration dominated the evaporation during the two sampling days. This result confirms that the method of irrigation applied by the farmer was very appropriate for conditions in the orchard, but that it is necessary to re-examine both the amount and timing of water applied through irrigation to minimize losses by percolation.

Key words: *evapotranspiration partitioning, water losses, stable isotopes, percolation, fluxmeter.*

INTRODUCTION

Arid and semi-arid regions constitute roughly one third of the total earth 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 percent of available water is used for irrigation in these regions. Sound and efficient irrigation practices are therefore important for achieving sustainable management of water resources in these regions. In this regard, a better understanding of the water balance is essential for exploring water-saving practices and to avoid contamination of groundwater. The most important components of water balance in semi-arid areas are evapotranspiration (ET) and deep percolation. Methods such as lysimetric and sap flow measurements and micrometeorological techniques are used to measure or estimate ET. These do, however, have limitations. Stable isotopic tracer methods offer new opportunities to study the components of ET at field scales, from the leaf to ecosystem levels, and can partition ET from different compartments of the ecosystem that incorporate water vapour.

MATERIALS AND METHODS

Study site

The study site was a mandarin (Afourer variety) orchard planted in July 2000. It is located approximately 30 km southwest of Marrakech city, Morocco (31°50′ 27″N, 008°25′ 02″W). This area has a semi-arid Mediterranean climate, characterized by low and irregular rainfall (annual average of about 240 mm) and a higher reference evapotranspiration (ET_0) of 1 600 mm per year. The trees were planted in a regular square pattern (4 m × 6 m), and were maintained in well-watered conditions by drip irrigation, supplied every day. Fertilization, pest and weed control were performed. The soils have high sand and low clay contents (18 percent clay, 32 percent silt, and 50 percent sand).

Meteorological data and reference evapotranspiration

The site was equipped with a set of standard meteorological instruments to measure wind speed and direction (model Wp200, R.M. Young Co., USA) as well as air temperature and humidity (model HMP45AC, Vaisala Oyj Finland) at four heights. Net radiation over the vegetation and soil was measured using net radiometers (model CNR1, Kipp and Zonen, The Netherlands and the Q7 net radiometer, REBS Inc., USA). Soil heat flux was measured using soil heat flux plates (Hukseflux). Water content reflectometers (CS616, Campbell Scientific Ltd., USA) 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., USA).

Eddy covariance measurements

An eddy-covariance (EC) system was installed over the citrus field to provide continuous measurements of vertical fluxes of heat (H_{EC}) and water vapour (L_vE_{EC}). The EC system consisted of commercially avail-

1 Water and Climate Unit, CNESTEN, Rabat, Morocco
2 Cadi Ayyad University, Marrakech, Morocco
3 Institut de Recherche pour le Développement (IRD), Morocco
4 Faculty of Science, Meknès, Morocco
* E-mail address of corresponding author: amenzou@cnesten.org.ma

L.K. Heng, K. Sakadevan, G. Dercon and M.L. Nguyen (eds), Proceedings — International Symposium on Managing Soils for Food Security and Climate Change Adaptation and Mitigation. Food and Agriculture Organization of the United Nations, Rome, 2014: 269–273

able instrumentation: a 3D sonic anemometer (CSAT3, Campbell Scientific Ltd., USA) and a fast response hygrometer (Campbell Scientific Inc., USA). Raw data were collected at a rate of 20 Hz and recorded using CR5000 data loggers (Campbell Scientific Ltd., USA). The half-hourly fluxes were later calculated off-line using EC processing software 'ECpack', after performing all required corrections for planar fit, humidity and oxygen (KH_2O), frequency response for slow apparatus and path length integration (Van Dijk, Moene and De Bruin, 2004).

Infiltration measurements using Fluxmeter

Besides the standard meteorological measurements, one flux meter was installed at a depth of 80 cm which corresponds to the root zone to quantify the water loss by deep percolation.

Stable isotope measurements

Soil and plant water and vapour collection

Using a hand auger, soil was sampled from the surface to a depth of 10 cm. Sampled branches of mandarin trees were 0.5–1.0 cm in diameter and 1–2 cm in length, and from each 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.

Water vapour was collected at five heights: 0.1 m, 1.75 m, 2.95 m, 4.45 m and 8.12 m. Sampling was carried out at 10:00, 11:00, 13:00, 14:00 and 15:00 h during the collection period mentioned above. For each group, vapour was collected using a vacuum pump for one hour with a flow rate of 250 mL/min. The air was circulated through a set of 45 cm long glass traps (modified from Helliker *et al.,* 2002) which were immersed in a mixture of ethanol and liquid nitrogen (at about –80°C). Traps were made of 9 mm diameter Pyrex glass attached to 6–9 mm diameter Cajon Ultra-Torr adapters which were framed in 9 mm diameter Swagelok Union Tee. After sampling the traps were sealed with parafilm and stored at about 2°C.

Probes of model HMP45AC, Vaisala Oyj, Finland for measuring the air temperature (T_a, in Kelvin) and relative humidity (h,) were placed near the vapour sampling inlets at 5 min intervals. Using T_a, h and atmospheric pressure (Pa, in hPa), water vapour concentration was calculated using Equation 1 (shown below; McRae, 1980):

$$H_2O\ (\text{mmol/mol}) = \frac{10h\left[P_a \exp(13.3185\,t - 1.99760\,t^2 - 0.6445\,t^3 - 0.1299\,t^4)\right]}{P_a} \quad (1)$$

where P_a = standard atmosphere pressure (about 1 013.25 hP_a) and $t = 1 - (373.15/T_a)$.

Keeling Plots were generated using the inverse of the average vapour concentration ($1/[H_2O]$) at each height as independent variables and isotopic composition of water vapour (delta oxygen-18 or deuterium, $\delta^{18}O$ or δD) collected at the corresponding height as dependent variables.

Stable isotope and data analysis

Soil and plant water were extracted by cryogenic vacuum distillation (Ehleringer, Roden and Dawson, 2000). Water samples were analysed isotopically at the National Center of Sciences and Nuclear Techniques (CNESTEN) by DLT-100 laser spectroscopy (±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 in per mil (‰) as deviations from an international standard (V-SMOW) and using the delta (δ) notation as follows:

$$\delta‰ = [(R_s/R_{st}) - 1] \times 1000 \quad (2)$$

where R_s and R_{st} were the ratios of the heavy to light isotopes in the sample and the standard, respectively.

RESULTS AND DISCUSSION

Evolution of climatic conditions

Figure 1 presents the variations in climatic variables during the 2009 growing season at the Agafay site. The lowest values for Ta occurred during the winter (4.4°C) and the highest were in the summer (43.5°C). Atmospheric humidity was low (56 percent), and global radiation was high in summer (606 Wm^2) and low in the winter (35 W/m^2). The wind speed was stable during all seasons (average 1.1 m/s). Rainfall was quite uneven and variable throughout the year.

Seasonal variations in the reference evapotranspiration ET_0 of well-watered grass were calculated using the FAO Penman–Monteith equation (FAO, 1998) using the meteorological parameters collected over the study site. The ET_0 pattern was characteristic of semi-arid continental climates, with an average accumulated annual ET_0 of 1355 mm. The lowest values occurred during the winter and

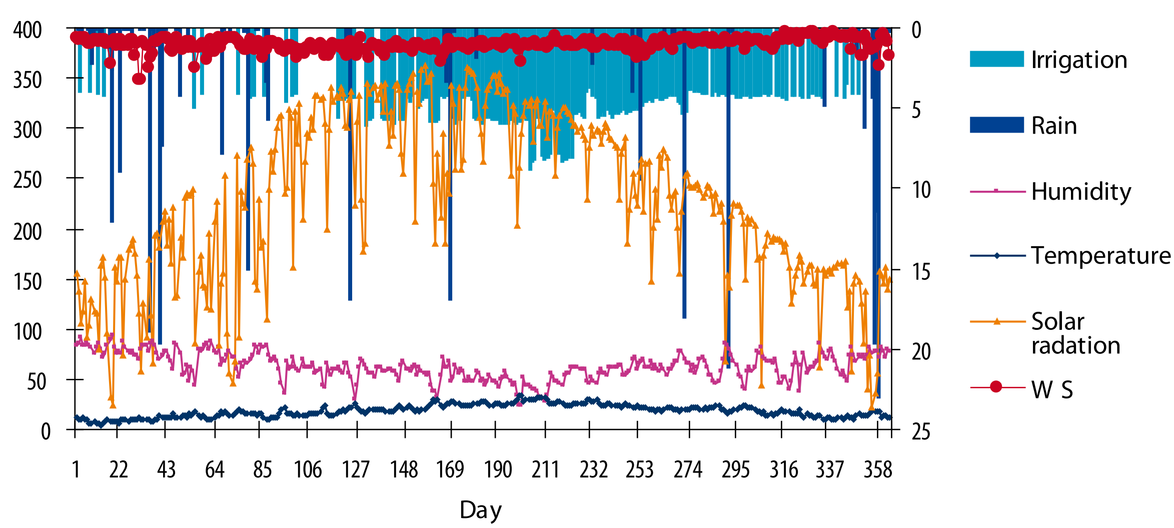


FIGURE 1. Variations in environmental conditions during the growing season of 2009.

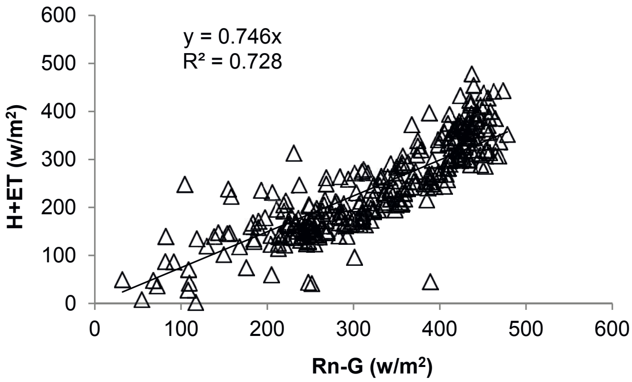


FIGURE 2. Daily energy balance closure.

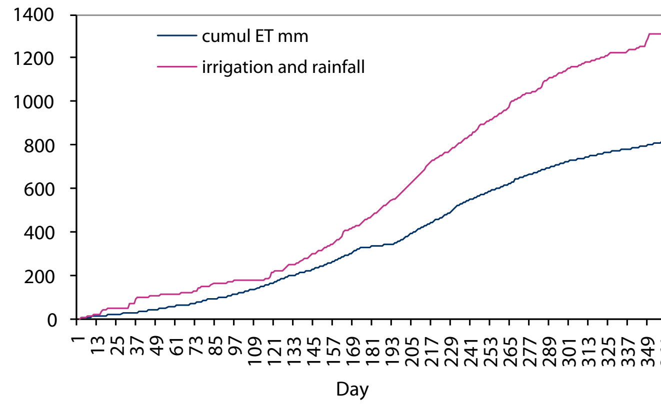


FIGURE 3. Cumulative evapotranspiration (ET) compared with the sum of the amounts of precipitation and irrigation.

autumn (0.05 mm/day) and the highest values were in the summer (11.07 mm/day).

Flux data quality assessment

Energy balance closure is an important indicator of the performance of an EC system. By assuming the principle of conservation of energy, the energy balance closure (*EC*) is defined as:

$$EC = R_n - H - ET - G \quad (3)$$

where R_n = net radiation; G = soil heat flux; and H and ET = sensible and latent heat fluxes derived from the EC.

Figure 2 presents a cross plot between measured ($R_n - G$) and the sum of the turbulent fluxes ($H + ET$). The difference in terms of the source areas of the different instruments has the greatest impact on the closure of the energy balance, especially over sparsely vegetated surfaces. The source area sampled by EC is much larger than that of net radiation and soil heat flux, and it can change rapidly depending on wind speed and direction and on surface conditions. However, compared with values reported in the literature, the closure can be considered as fairly acceptable.

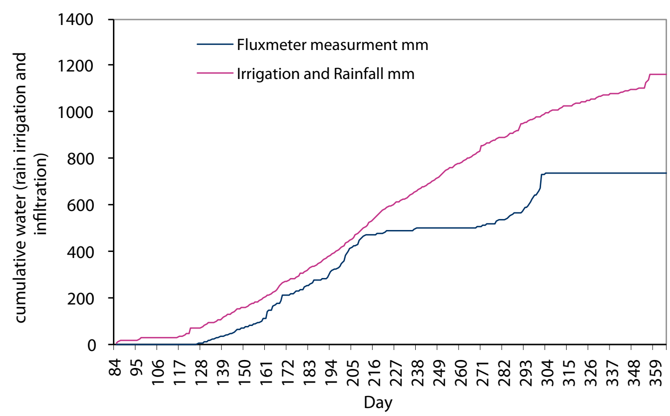


FIGURE 4. Cumulative water drainage compared with the sum of precipitation and irrigation.

Losses by infiltration.

Losses through infiltration were evaluated using the water balance equation method and directly using a fluxmeter.

Water balance measurements (EC system)

This method consists of comparing the cumulative evapotranspiration measured by EC and the sum of the cumulative amounts of irrigation and rainfall. Total rainfall during the experiment was 295 mm, while the average annual rainfall in the Tensift river basin is 240 mm. Figure 3 shows that about 495 mm was lost by infiltration and runoff during this season, representing 38 percent of the sum of irrigation and rain.

Direct and indirect estimation of infiltration

Values for cumulative infiltration and the cumulative totals for irrigation and rain (Figure 4) show that water lost by deep infiltration was about 425 mm, representing 32 percent of the sum of cumulative rain and irrigation. The difference between direct measurement of percolation and that derived from the water balance can be explained by surface runoff during rain events. This result is consistent with that obtained using the water balance equation, and reveals that the farmer applied a large amount of water. Therefore, it is necessary to re-examine the amount of water applied and the timing of irrigation.

Partitioning evapotranspiration components

The stable isotopic composition of water vapour, stem and soil water

Isotopic compositions of soil water (δ_S) ranged from -6.33‰ to -4.36‰ for $\delta^{18}O$, and from –54.31‰ to –30.2‰ for δD. Isotopic ratios of stem water (δT_S) ranged from –6.19‰ to –5.27‰ for $\delta^{18}O$, and from –45.25‰ to –43.47‰ for δD. Isotopic compositions of vapour (δa) ranged from –11.32‰ to –7.81‰ for $\delta^{18}O$, and from –73.05‰ to –59.68‰ for δD. These results indicate that the isotopic values of water vapour evaporating from the soil surface (δ_E, soil evaporation) were more isotopically depleted relative to vapour generated by plant transpiration (δ_T) during the two sampling days. All samples (vapour, soil water, stem water, irrigation water) were situated around the local meteoric water line (LMWL). The regression line of all samples intersected the LMWL at the point that presented the origin of all samples.

Keeling plot analysis

The isotopic ratio of atmospheric water vapour at a certain altitude can be described using Equation 4 by considering the mixing of evapotranspired water vapour and free atmospheric water vapour (Keeling, 1958; Moreira *et al.,* 1997). This relationship is linear and

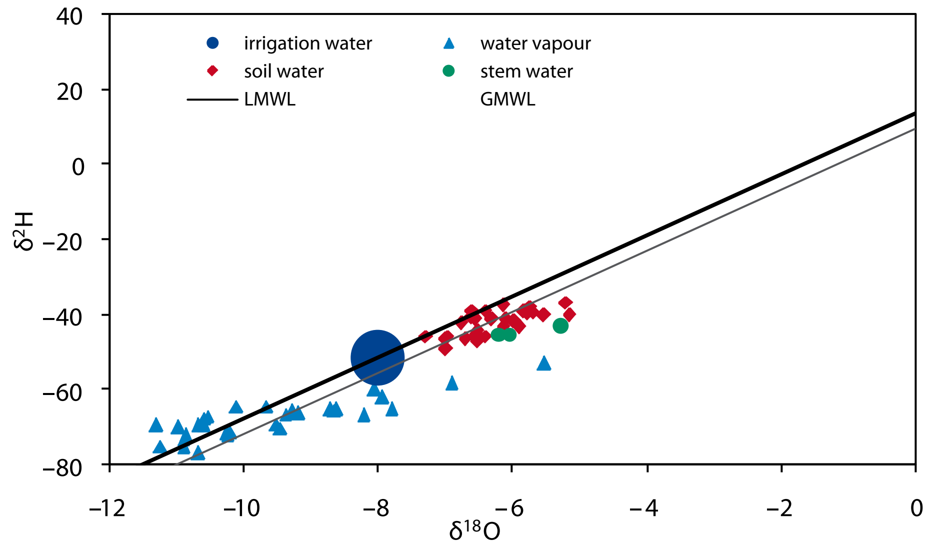


FIGURE 5. $\delta^{18}O$ versus δD in atmospheric water vapour, irrigation water, stem water and soil water at the Agafay site.

when used with water vapour the *y*-intercept reflects the source isotopic composition of the evapotranspiration flux:

$$\delta_{ebl} = C_a\,(\delta_a - \delta_{ET})\,\frac{1}{C_{ebl}} + \delta_{ET} \qquad (4)$$

where δ_{ebl} = isotopic composition of vapour collected from the ecosystem boundary layer; C_a — atmospheric vapour concentration; C_{ebl} — vapour concentration in the ecosystem boundary layer; δ_a —isotopic composition of the atmospheric background; and δ_{ET} — 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 sources within the ecosystem. It is further assumed that the only loss of water vapour from the ecosystem is by turbulent mixing with the background atmosphere.

The isotopic ratio of evaporated water vapour from the soil surface is described by considering the fractionation process (Craig and Gordon, 1965) as:

$$\delta_E = \frac{\alpha^*\delta_{surf} - h\delta_{atm} - \varepsilon_{eq} - (1-h)\,\varepsilon_k}{(1-h) + (1-h)\,\varepsilon_k\,\frac{\varepsilon_k}{100}} \qquad (5)$$

where δ_E — isotopic composition of soil evaporation flux; α^* —the temperature-dependent equilibrium fractionation factor; ε_k — kinetic fractionation factor; h — relative humidity normalized to the temperature at the evaporation surface in soil; δ_{atm} —isotopic composition of atmospheric vapour; and δ_{surf} — isotopic composition of water at the evaporation surface in soil.

In this paper, $\alpha^* = 1/\alpha^+$ (Gat and Matsui, 1996) and α^+ can be calculated by Equations 5 and 6 provided by Majoube (1971):

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

$$D\alpha^* = [24.844\,(10^6/T^2) - 76.248\,(10^3/T) - 52.612]1000 + 1 \qquad (7)$$

where T = soil temperature recorded at 5 cm depth in degrees Kelvin and ε_k is estimated using the diffusivity ratios of 1.0251 for H_2O:HDO and 1.0281 for H_2O:$H_2{}^{18}O$ (Merlivat, 1978).

The contribution of transpiration to evapotranspiration (F_T) was estimated by Yakir and Sternberg (2000) as:

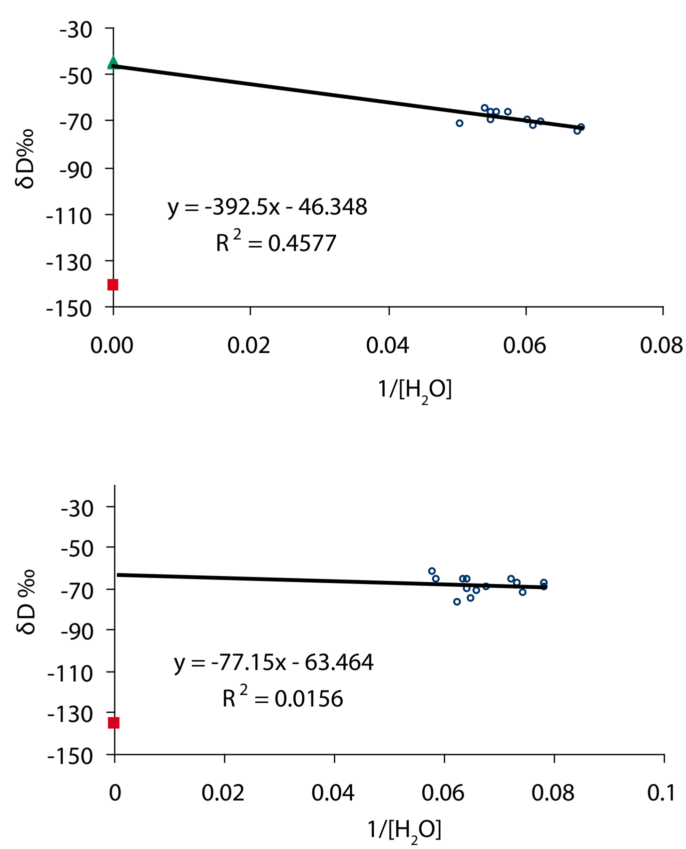


FIGURE 6. Relationship between δD at different levels above ground and the inverse of air absolute humidity at the Agafay site (A 16/07/2009, B 17/07/2009) (E = evaporation, T= transpiration).

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 compositions of evapotranspiration (δET).

	δs	δa	δ_T	δ_{ET}	R^2	p	n	δ_E	T/ET
16/07/2009	-41.4	-65.1	-44.6	-46.3	0.457	0.022*	11	-140.5	0.982
17/07/2009	-46.14	-68.5	-45.1	-63.5	0.015	0.67	14	-134.9	0.795

* The significance level is 0.05

$$F_T = \frac{\delta_{ET} - \delta_E}{\delta_T - \delta_E} \quad (8)$$

Figure 6 shows the relationship between the δ_D values of ambient vapour and the inverse of its absolute humidity while Table 1 shows the mathematical treatment for data obtained from Figure 6, including the slope and intercept of the regression equations between the δ_D values of vapour and the inverse of absolute humidity.

A significant correlation between isotopic values and the inverse of vapour concentrations was observed only for the first day of sampling. The intercepts of the regression lines at Agafay show a high transpiration contribution for the mandarin vapour, suggesting that this source plays an important role in the water cycle.

Considering mandarin crop transpiration as one source and soil evaporation as another, the fractional contribution of plant transpiration to total ET (T/ET) varied between 98 percent and 79.5 percent for δD during the two days of sampling. Consequently, transpiration dominated the evaporation, a result confirming that the irrigation method applied by the farmer was very appropriate for the conditions in the orchard and considering evaporation as the only source of water loss.

CONCLUSIONS

Stable isotope contents and Keeling plots allowed the partitioning of ET into different flux components in a citrus orchard irrigated with drip irrigation. The results obtained on two sampling days during July 2009 indicated that more than 80 percent of ET was generated by plant transpiration, from which it can be concluded that evaporation was negligible. However, loss by drainage was more important, contributing about 38 percent of total losses from the total cumulative irrigation and rainfall. This percolation, which depends closely on the irrigation, was accentuated by the addition of rainfall.

These results confirm that by considering only evaporative losses the efficiency of the irrigation system applied on the Agafay station was high. However, the results also showed that large quantities of water were lost by percolation, infiltration and runoff. The farmer should therefore re-consider both the amount of water applied and the timing of irrigation in order to minimize such losses.

ACKNOWLEDGMENTS

This research was conducted within the framework of an FAO/IAEA Coordinated Research Project on “Managing irrigation water to enhance crop productivity under water-limiting conditions: A role for isotopic techniques”. We are grateful to the International Atomic Energy Agency (IAEA), in particular Mr. Long Nguyen and Ms. L.K. Heng for their scientific and technical support.

REFERENCES

Craig, H. & Gordon, L.I. 1965. *Deuterium and oxygen-18 variations in the ocean and the marine atmosphere. In* E. Tongiorgi, ed. Proceedings of the Conference on Stable Isotopes in Oceanographic Studies and Paleotemperatures, pp. 9–130. Pisa, Laboratory of Geology and Nuclear Science.

Ehleringer, J.R., Roden, J. & Dawson, T.E. 2000. *Assessing ecosystem-level water relations through stable isotope ratio analysis. In* O.E. Sala, R.B. Jackson, H.A. Mooney & R.W. Howarth eds. *Methods in ecosystem science*, pp. 181–198. New York, Springer.

FAO. 1998. *Crop evapotranspiration–guidelines for computing crop water requirements,* by R.G.Allen, L.S. Pereira, L.S., D. Raes, & M. Smith. FAO Irrigation and Drainage Paper 56. Rome.

Gat, J.R. & Matsui, E. 1991. Atmospheric water balance in the Amazon basin: An isotopic evapotranspiration model. *J. Geophys. Res.*, 96: 13179–13188.

Helliker, B.R., Roden, J.S., Cook, C. & Ehleringer, J.R. 2002. A rapid and precise method for sampling and determining the oxygen isotope ratio of atmospheric water vapor. *Rapid Commun. Mass Spectrom.*, 16: 929–932.

Keeling, C.D. 1958. The concentration and isotopic abundance of atmospheric carbon dioxide in rural areas. *Geochim. Cosmochim. Acta,* 13: 322–334.

Majoube, M. 1971. Fractionnement en oxygene-18 et en deuterium entre l’eau et sa vapeur. *J. Chimie Physique,* 68: 1423–1436.

McRae, G.J. 1980. A simple procedure for calculating atmospheric water vapor concentration. *J. Air Pollut.Contr. Assoc.,* 30: 394–396.

Merlivat, L. 1978. Molecular diffusivities of $H_2{}^{16}O$, $HD^{16}O$, and $H_2{}^{18}O$ in gases. *J. Chem. Phys.,* 69: 2864–2871.

Moreira, M.Z., Sternberg, L.D.S.L., Martinelli, L.A., Victoria, R.L., Barbosa, E.M., Bonates, L.C.M. & Nepstad, D.C. 1997. Contribution of transpiration to forest ambient vapour based on isotopic measurements. *Global Change Biol.*, 3: 439–450.

Van Dijk, A., Moene, A.F. & De Bruin, H.A.R. 2004. *The principles of surface flux physics: Theory, practice and description of the ECPACK library*. Internal Report 2004/1. Meteorology and Air Quality Group, Wageningen University, Wageningen, The Netherlands. 99 pp.

Yakir, D. & L.D.S.L. Sternberg. 2000. The use of stable isotopes to study ecosystem gas exchange. *Oecologia,* 123: 297–311.

Effects of Climate and Soil Management on Crop Water Use Efficiency: The Role of Modelling

E. Wang[1,*], Z. Zhao[1,2], C. Chen[3] and C.J. Smith[1]

ABSTRACT

Water scarcity is the major limitation to crop production in many parts of the world. The water use efficiency (WUE) by which crops use rainfall and irrigation water to produce grains is regulated by climate and soil conditions during the crop growing season. This paper briefly depicts how crop WUE is regulated by climate and soil, and demonstrates that crop modelling provides an effective means to benchmark crop WUE as influenced by climate change and soil management practices. Comparison of the modelled WUE against what is observed in the field enables the assessment of WUE and yield gaps, and possible management options to increase both WUE and yield. While water loss by evaporation from soil is a major factor reducing crop WUE, and it increases in drier climates, improvement in technologies to quantify crop transpiration and soil evaporation, and measures to reduce soil evaporation can help to identify approaches to increase crop WUE.

Key words: *Water productivity, wheat, Murray Darling Basin, North China Plain, transpiration, evaporation.*

INTRODUCTION

Water is a major limiting factor to crop production in many parts of the world, particularly in semi-arid and arid regions, which occupy around one third of the Earth's land surface. Although low water availability is often associated with high climate (rainfall) variability, it also coincides with abundant radiation and high crop yield potential on good soil under irrigation. Improved management of climate variability and soil fertility then becomes essential to ensure efficient use of the limited water resources. This, however, is a challenging task because crop yield is a result of integration of climate, soil and management conditions over the whole growing season. The overall crop water use efficiency (WUE, i.e. crop yield produced per mm of water used) depends not only the amount, but also the timing of water supply (rainfall or irrigation), and the capacity of the soil to hold water for plant use.

Soil–plant systems modelling can play a key role in understanding the interactions between climate and soil as they impact on WUE. A crop model integrates the current understanding of crop physiological processes, and is able to dynamically simulate crop growth, development and yield formation in response to seasonal changes in weather, soil and management conditions. It provides an effective means to identify constraints to crop yield and to evaluate management strategies for increasing crop productivity and WUE. This paper briefly explains how crop WUE is regulated by climate and soil conditions and demonstrates how crop modelling helps to define the crop yield potential and the water use efficiency frontier (WUE maximum), and to identify yield constraints and management strategies to increase crop WUE.

MATERIALS AND METHODS

Roles of climate and soil to regulate WUE

Crops transpire water (H_2O) while they assimilate carbon dioxide (CO_2) mainly through stomatal control, to produce biomass and grain. Combining the diffusion equations of H_2O and CO_2 through leaf, canopy characteristics and bio-composition of a crop, it can be shown that crop transpiration efficiency (ε, the amount of water transpired to produce unit amount of biomass, B_m) is a function of crop type, daytime vapour pressure deficit (D) and CO_2 concentration in the air (C_a) (Sinclair, Tanner and Bennett, 1984; Wang *et al.*, 2004):

$$\varepsilon = \frac{B_m}{T} = abc\frac{C_a}{D} = \beta\frac{C_a}{D} \quad (1)$$

where a is a constant derived from the molecular weight of H_2O and CO_2 and canopy leaf structure; b is the conversion coefficient of hexose to plant biomass; and c accounts for the ratio of CO_2 partial pressure inside and outside leaf. $\beta = abc$ is then a crop-dependent coefficient.

Equation 1 is easily applied on a daily basis. If B_m and T are the total biomass and transpiration of the whole growing season, β and D need to be representative for the whole season, their calculation procedures become more complex. Nonetheless, the equation still applies. It turns out that $\beta = abc$, is relatively constant for a given crop species, thus the biomass produced (B_m) or crop grain yield (Y) is directly proportional to the amount of water transpired (T) and *vice versa*. If $Y = H_iB_m$, where H_i is the harvest index, then:

$$Y = H_iB_m = H_iT\varepsilon = T\left(H_i\beta\frac{C_a}{D}\right) \quad (2)$$

If crop WUE is defined as grain yield per unit water input (the sum of precipitation P and irrigation I), $f(T)$ and $f(ET)$ are the fraction of crop transpiration in total evapotranspiration (ET) and the fraction of ET in total water inputs ($P+I$), it gives:

$$WUE = \frac{Y}{P+I} = H_i\varepsilon\left(\frac{T}{ET}\right)\left(\frac{ET}{P+I}\right) = H_i\beta\frac{C_a}{D}f(T)f(ET) \quad (3)$$

It follows that: (i) WUE is directly related to transpiration efficiency (ε), therefore it increases with atmospheric CO_2 concentration but decreases with the dryness of the air (D), (ii) WUE is crop-dependent

1 CSIRO Land and Water, Black Mountain, Canberra, ACT 2601, Australia
2 China Agricultural University, Beijing 100093, China
3 University of Technology, Sydney, NSW 2007, Australia
* E-mail address of corresponding author: enli.wang @csiro.au

L.K. Heng, K. Sakadevan, G. Dercon and M.L. Nguyen (eds), Proceedings — International Symposium on Managing Soils for Food Security and Climate Change Adaptation and Mitigation. Food and Agriculture Organization of the United Nations, Rome, 2014: 275–278

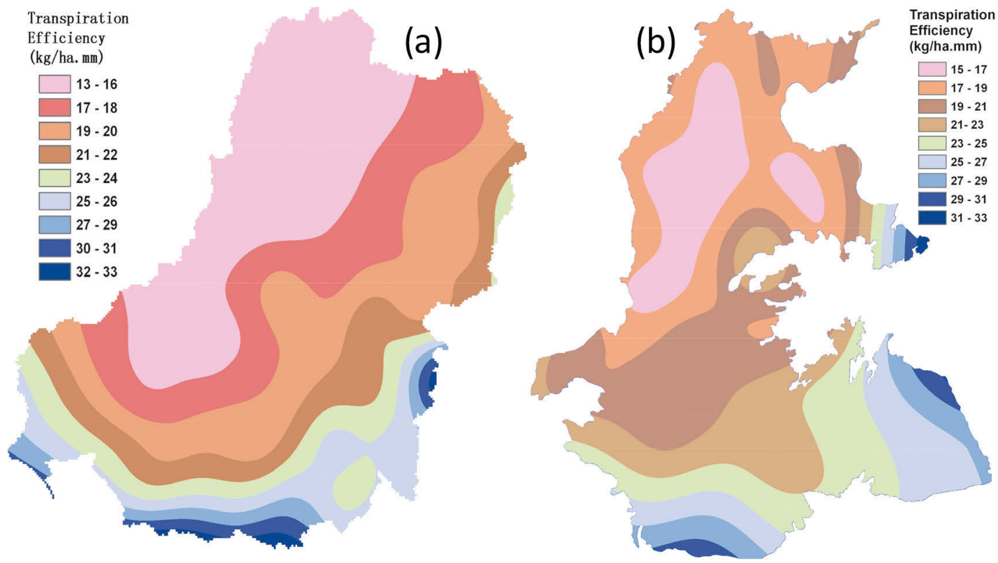


FIGURE 1. Average whole season transpiration efficiency of wheat crop at Murray Darling Basin of Australia (a) and the North China Plain (b).

(β, H_i) and increases with crop harvest index (H_i), and (iii) WUE can be increased through increasing the fraction of transpiration *f*(*T*) and evapotranspiration and *f*(*ET*).

Experimental results also show that higher CO_2 concentrations tend to increase leaf and plant level WUE (Eamus, 1991). Breeding efforts for new crop varieties have increased crop harvest index (H_i) continuously leading to significant increases in crop yields and WUE (Liu *et al.,* 2010; Liu *et al.,* 2012).

Soil regulates WUE through its capacity to store or hold water for plant use. Soils that enable more water to infiltrate and that have larger plant available water holding capacity (PAWC) reduce water losses by surface runoff and deep drainage, thus increasing *ET* and crop transpiration (*T*), i.e. both *f*(*T*) and *f*(*ET*), particularly in areas with higher rainfall variability (Wang *et al.*, 2009). Management practices to reduce soil evaporation (*E*) further improve WUE through increasing *T*.

Crop modelling

The Agricultural Production Systems Simulator APSIM (Wang *et al.*, 2002; Keating *et al.*, 2003) was used to simulate wheat grain yield and WUE across climatic regions and on several soil types to demonstrate how modelling can help define the WUE frontiers. The wheat module in APSIM (APSIM-Wheat; Wang *et al.*, 2003), simulates wheat growth, development and yield formation on a daily time step in response to climatic and soil conditions and management interventions. It has been tested extensively in Australia (Wang *et al.*, 2003; Hochman, Holzworth and Hunt, 2009) and China (Chen, Wang and Yu, 2010), and has shown good performance in predicting wheat yield and water use under different rainfall conditions and irrigation levels.

The Murray Darling Basin (MDB) in Australia and the North China Plain (NCP) were used as study areas to sample the climate impact on WUE. The Agricultural Production Systems Simulator was run with a commonly used wheat cultivar "Janz" in MDB and "Zhixuan 1" in NCP to grow on a representative soil with PAWC (to 150 cm depth) of 233 mm in MDB and 350 mm in NCP, respectively. Wheat was simulated in a single cropping system (sowing wheat every yr) in MDB for 101 years from 1891 to 2002, while in a double cropping system (wheat–maize) in NCP for 50 years from 1961 to 2010. Inter annual rainfall variability is high in both MDB and NCP. Average annual rainfall in MDB decreased from >1 000 mm in the east to <300 mm in the west areas, while in NCP it decreased from > 900 mm in the southeast to <500 mm in the northwest during the simulation periods. The simulation results enabled the whole season crop transpiration efficiency (ε) to be defined. For each site, it was calculated as the slope of regression line between the grain yield (*Y*) and the growing season transpiration (*T*) from the simulation results, representing average transpiration efficiency over the yr of simulation.

In MDB, wheat is normally grown in dryland conditions, and the yield directly responds to rainfall. The impact of different soils (PAWC range of 70–260 mm) on wheat yield was investigated at a selected site Young (wheat season rainfall 406 mm). In NCP, on the other hand, most wheat is grown under irrigation. The wheat yield response to different levels of irrigation water supply was also studied (range of 60–420 mm of irrigation) at Luancheng (wheat season rainfall 146 mm).

RESULTS AND DISCUSSION

The whole season crop transpiration efficiency (ε) is the grain yield produced per mm of water transpired by the wheat crop. It represents the maximum value of crop WUE under the current climate if all water (*P* + *I*) can be used by plant via transpiration. It can be used as a benchmark of crop WUE across the study regions. In both MDB and NCP, it had a similar range of 15–33 kg·grain·ha^{-1}·mm^{-1} (Figure 1), and decreased from southeast to northwest regions, roughly following the spatial distribution pattern of wheat season rainfall.

The spatial pattern of the whole season transpiration efficiency clearly shows the climate regulation of WUE. This pattern indicates that much more water is required in drier areas to produce per kg of wheat grain. In the humid area of both MDB and NCP (ε = 30 kg grain·ha^{-1}·mm^{-1}), to produce a wheat grain yield of 5 Mg/ha, 167 mm of water needs to be transpired by the crop. In the driest area (ε = 15 kg·grain·ha^{-1}·mm^{-1}), twice as much water (333 mm) would be needed to produce the same wheat grain yield.

The role of soil in regulating WUE is illustrated by the simulation results with different soils at Young in MDB. Under the same climate and wheat season rainfall (average of 406 mm), soils with higher

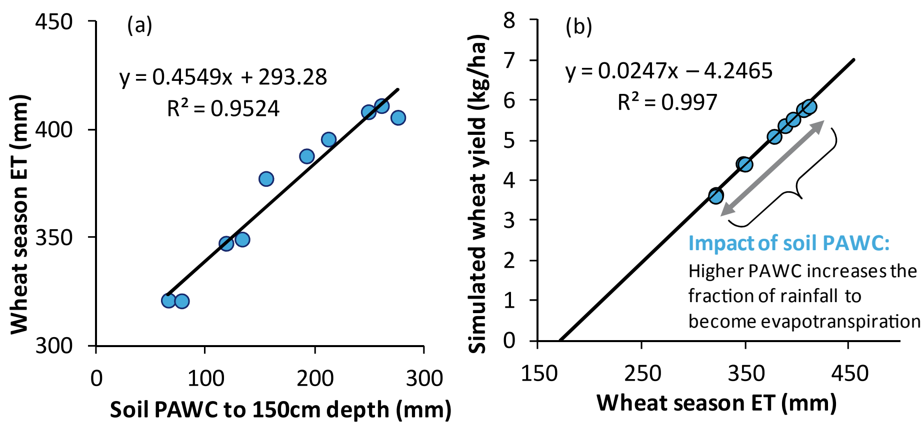


FIGURE 2. Impact of PAWC of soils on wheat growing season evapotranspiration (ET) (a) and the relationship between dryland wheat yield and wheat season ET (b) at Young, NSW, Australia. Dots are the average values calculated based on 101 yr of simulation results. Lines are regression lines. In (b) the slope of the regression line is the whole season transpiration efficiency of wheat.

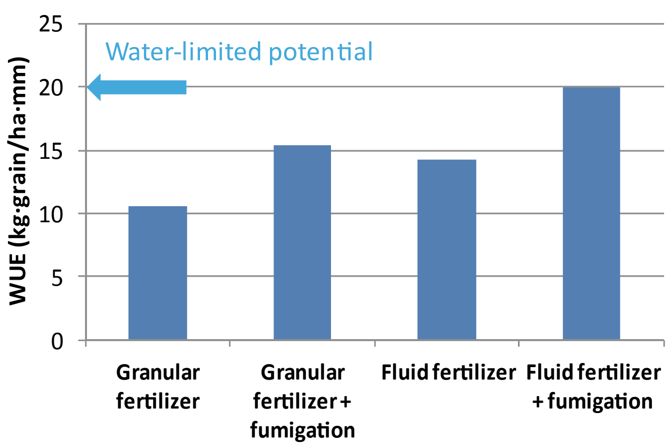


FIGURE 3. Impact of application of granular fertilizer, liquid fertilizer and fumigation on wheat WUE. Results are from an experiment conducted at Eyre Peninsula South Australia.

PAWC hold more water from the variable rainfall for a longer time to allow crop water uptake, leading to increased crop season evapotranspiration (*ET*) and subsequently higher wheat grain yield (Figure 2). Increase of soil PAWC from 80 mm to 260 mm (representing a change from a shallow soil to a deep soil) would result in a 28 percent increase in wheat season *ET* (Figure 2a), corresponding to a 62 percent increase in wheat grain yield and whole season wheat WUE (Figure 2b).

Changes in soil PAWC did not change the crop transpiration efficiency (ε = the slope of the line in Figure 2b). Rather, it increased crop season *ET* and subsequently crop transpiration (*T*). As a result, both $f(T)$ and $f(ET)$ in equation (3) were increased.

Once a benchmark WUE is defined based on the local climatic and soil conditions, it can be used to identify other constraints to crop yield and to explore management options that can reduce or eliminate these constraints to increase crop yield and WUE. Figure 3 shows an example where the benchmark WUE was 20 kg·gain·ha^{-1}·mm^{-1}, but both nutrient supply and soil disease limit crop yield. Use of liquid fertilizers plus fumigation of the soil enabled the WUE to reach the benchmark value.

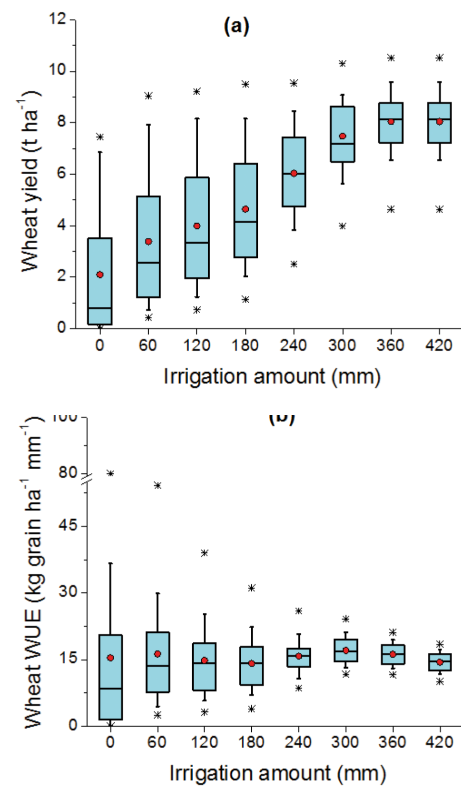


FIGURE 4. Impact of irrigation on simulated wheat yield (a) and wheat whole season WUE (b) at Luancheng in NCP. In (a) the box plots show the 0, 10, 25, 50, 75, 90 and 100 percentiles. The circles in the box plots show the average.

Figure 4 shows the change in simulated wheat yield in response to irrigation water supply at Luancheng in NCP. Inter-annual climate (rainfall) variability had a significant impact on wheat yield as shown by the ranges of the box plots (Figure 4a). Increasing irrigation resulted in both increased average wheat yield and in reduced yield variability between the yr. The results clearly show that up to 360 mm of irrigation water would be needed to achieve the maximum wheat yield (Figure 4a). However, WUE would decrease if irrigation water supply exceeded 300 mm (Figure 4b). The results in Figure 4 enable optimization of irrigation scheduling depending on whether to achieve maximum yield or maximum WUE, or maximum profit if grain and water prices were available.

Evaporation loss from soil was simulated to be a major loss that reduced the wheat WUE. The fraction of evaporation in total crop evapotranspiration increased from around 30 percent in high rainfall areas to 70–80 percent in low rainfall areas under dryland conditions in both MDB and NCP. Therefore, preventing evaporation loss through mulching or other measures remains an effective means to increase WUE; the drier the area is, the more effective is reducing evaporation to increase grain yield. Using isotopes of hydrogen-2 (^{2}H) and oxygen-18 (^{18}O) to partition evapotranspiration into evaporation and transpiration can help to quantify what is achievable under different cropping systems across different climatic regions.

CONCLUSIONS

In semi-arid and arid areas, crop yield is directly proportional to the amount of water transpired by the crop. The crop transpiration efficiency is regulated by climate through the CO_2 concentration in the air and air dryness (vapour pressure deficit). Soil regulates crop WUE through its capacity to store rainfall (and irrigation) for use by crop and through its nutrient levels to support crop growth. Crop modelling provides an effective means to benchmark crop WUE under various climatic and soil conditions. Comparison of benchmarks with what is observed in the field enables the identification of WUE and yield gaps, and management options to increase both yield and WUE. While water loss from evaporation from soil is a major factor reducing crop WUE, improvement in technologies to quantify crop transpiration and soil evaporation, and measures to reduce evaporation from soil can help to identify approaches to increase crop WUE.

ACKNOWLEDGEMENT

This study was supported by CSIRO and the Chinese Academy of Sciences (CAS) through the research project "Advancing crop yield while reducing the use of water and nitrogen", by the National Basic Research Program of China (973 Program, 2012CB955904), by the Earmarked Fund for Modern Agro-Industry Technology Research System (CAR4-3), China, and by CSIRO and the Chinese Ministry of Education (MoE) through the CSIRO-MoE PhD Research Programme. Financial support from the above sources is gratefully acknowledged.

REFERENCES

Chen, C., Wang, E. & Yu, Q. 2010. Modeling wheat and maize productivity as affected by climate variation and irrigation supply in North China Plain *Agron. J.,* 102: 1037–1049.

Eamus, D. 1991. The interaction of rising CO_2 and temperatures with water use efficiency. *Plant Cell Environ*., 14: 843–852.

Hochman, Z., Holzworth, D. & Hunt, J.R. 2009. Potential to improve on-farm wheat yield and WUE in Australia. *Crop Pasture Sci.*, 60: 708–716.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M. & Smith, C.J. 2003. An overview of APSIM, a model designed for farming systems simulation. *Eur. J. Agron.*, 18: 267–288.

Liu, Y., Wang, E., Yang, X. & Wang, J. 2010. Contributions of climatic and crop varietal changes to crop production in the North China Plain, since 1980s. *Global Change Biol.*, 16: 2287–2299.

Liu, L., Wang, E., Zhu, Y. & Tang, L. 2012. Contrasting effects of warming and autonomous breeding on single-rice productivity in China. *Agric. Ecosys. Environ.,* 149: 20–29.

Sinclair, T.R., Tanner, C.B. & Bennett, J.M. 1984. Water-use efficiency in crop production. *BioScience,* 34: 36–40.

Wang, E., Cresswell, H., Xu, J. & Jiang, Q. 2009. Capacity of soils to buffer impact of climate variability and value of seasonal forecasts. *Agric. Forest Meteorol.,* 149: 38–50.

Wang, E., Robertson, M.J., Hammer, G.L., Carberry, P.S., Holzworth, D., Meinke, H., Chapman, S.C., Hargreaves, J.N.G., Huth, N.I. & McLean, G. 2002. Development of a generic crop model template in the cropping system model APSIM. *Eur. J. Agron.*, 18: 121–140.

Wang, E., Smith, C.J., Bond, W.J. & Verburg, K. 2004. Estimations of vapour pressure deficit and crop water demand in APSIM and their implications for prediction of crop yield, water use, and deep drainage. *Aust. J. Agric. Res.*, 55: 1227–1240.

Wang, E., van Oosterom, E., Meinke, H., Asseng, S., Robertson, M., Huth, N., Keating, B. & Probert, M. *provements. In* M. Unkovich &G. O'Leary, eds. Proceedings 11th Australian Agronomy Conference. Australian Society of Agronomy, Geelong, Victoria, Australia. (http://www.regional.org.au/au/asa/2003/p/2/wang.htm)

Environmental Sustainability of Vegetable Production above a Shallow Aquifer

V. Zupanc[1,*], M. Šturm[2], S. Lojen[2], N. Maršić-Kacjan[1], J. Adu-Gyamfi[3], B. Bračič-Železnik[4], J. Urbanc[5] and M. Pintar[1]

ABSTRACT

Irrigation and fertilization techniques were evaluated over a two-year study period in terms of yield and environmental sustainability at a benchmark site near water protection zones above a shallow aquifer. For vegetables with a short growing period, three irrigation and fertilization treatments were applied in 2006 and 2007: (i) fertilization and 100 percent drip irrigation (fertigation), (ii) the farmer's practice (sprinkler irrigation) and fertilization, and (iii) control (the farmer's practice of irrigation, no fertilization). Equivalents of 80 and 200 kg/ha of nitrogen (N), 50 and 80 kg/ha of phosphorus (P), and 120 and 300 kg/ha of potassium (K) were added for endive and cabbage, respectively. Nitrogen-15 labelled fertilizer was used as a tracer. Results showed that environmentally sustainable practices (split application of nutrients compared with broadcast incorporating fertilization) in a humid climate can and should be a practice of choice on soils in water protection zones. The findings showed that fertigation is an effective way of minimizing nitrate leaching, and should be considered for vegetable production in or close to groundwater protection zones.

Key words: *irrigation, nitrate leaching, environmental sustainability, fertigation.*

INTRODUCTION

With impending climate change, agriculture will face extremely variable climatic conditions — periods of exceptionally high air temperatures and drought followed by periods of extremely high precipitations. Water deficit impedes nutrient uptake (Pandey, Maranville and Chetima, 2000), and unused fertilizer moves with deep percolation toward aquifers. Under such climatic conditions shallow aquifers are vulnerable to nitrate pollution (Almasri and Kaluarachchi, 2005; Burkart and Stoner, 2008), due to the proximity of the groundwater table, high nitrogen (N) fertilizer inputs in intensive vegetable production areas as well as inputs from urban and industrial pollution (Egboka, 1984). In order to preserve groundwater as a drinking water source, legislation requires strict measures on agriculture, severely limiting or banning fertilization of agricultural land on water protection zones. Effective irrigation, temporally and spatially adjusted to plant demands, decreases nitrate leaching to groundwater (Zupanc *et al*, 2011) and could enable agricultural production above water protection zones.

In an experiment conducted in the vicinity of a water protection zone in Slovenia, different irrigation and fertilization techniques for production of vegetables with a shorter growing period were tested under controlled conditions in a humid climate.

MATERIALS AND METHODS

On the alluvial plains of Ljubljansko polje, Slovenia (46°5′ N, 14°36′ E), three irrigation and fertilization treatments were applied to vegetables with a short growing period: (i) fertilization and 100 percent drip irrigation (fertigation), (ii) the farmer's practice of irrigation (sprinkler irrigation using water stored in plastic tanks) and fertilization (broadcast), and (iii) control (the farmer's practice of irrigation but no fertilization). The equivalents of 80 and 200 kg/ha of nitrogen (N), 50 and 80 kg/ha of phosphorus (P) and 120 and 300 kg/ha of potassium (K) were applied respectively to endive *(Cichorium endivia L.)* in 2006 and to cabbage *(Brassica oleracea* var. *capitata*) in 2007. Nitrogen-15 (^{15}N) labelled fertilizer as KNO_3 was used as a tracer. Fertilized plots (6.5 m^2) were divided into three sub-plots (2.6 m^2), and the labelled fertilizer was applied in the middle of the sub-plot (Šturm *et al.*, 2010). The labelled KNO_3 and the unlabelled water soluble $Ca(NO_3)_2$ were dissolved in tap water, then applied as a solution with a final relative ^{15}N concentration of 3.52 ± 0.04 atom percent. For the plots with the farmer's practice of fertilization, unlabelled $Ca(NO_3)_2$ (0.365 at. percent ^{15}N) was broadcast, followed by application of the labelled fertilizer as a solution. It was assumed that $Ca(NO_3)_2$, which was applied as a broadcast application the day before transplanting, was dissolved after the irrigation within a few hours and mixed with the labelled fertilizer in the soil (Zupanc *et al.*, 2011).

The irrigation regime was adjusted to the actual weather conditions in the field. Due to the wet weather in August and September 2006, the N fertilizer was applied to endive only twice, once before planting and once as a solution with 20 mm of water 23 d after transplanting. Fertilizer for cabbage was applied four times for the fertigation treatment: once before planting, and three times during the growing period via solution at 57, 66, and 75 d after transplanting (Šturm *et al.*, 2010). For the farmers' practice, each crop was irrigated with 50 mm of water one d before and 50 mm of water one d after transplanting using a tank sprinkler.

Soil was a gleyic Fluvisol and endogleyic Fluvisol, with a loam and sandy loam texture (Table 1), and a layer > 80 percent of sand

1 University of Ljubljana, Biotechnical Faculty, Agronomy Department, Ljubljana, Slovenia
2 Jožef Stefan Institute, Department of Environmental Sciences, Ljubljana, Slovenia
3 Soil and Water Management & Crop Nutrition Laboratory, International Atomic Energy Agency, Vienna, Austria
4 Drinking Water and Sewerage System Public Utility, Ljubljana, Slovenia
5 Geological Survey of Slovenia, Ljubljana, Slovenia
* E-mail address of corresponding author: vesna.zupanc@bf.uni-lj.si

TABLE 1. Soil layer depth (cm), total N (%), soil texture and bulk density (g/cm^3) on the experimental site above a shallow aquifer in Slovenia

Depth (cm)	N total (%)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g/cm)
0–20	0.12–0.18	37.7–39.1	47.9–48.8	13.0–13.8	1.34
20–35	0.05–0.12	40.2–56.9	33.3–36.2	9.8–11.2	1.42
35–60	—	83.6–87.4	9.1–13.2	2.6–3.2	1.38
60–100	—	57.2–71.4	23.0–36.2	3.5–8.6	1.27

appearing at the depth of 30 cm. Physical and chemical properties of the soil are presented in Table 1.

Soil water balance was calculated from continuous soil water measurements at different depths (10, 30, 50, 70 and 100 cm) using a time domain reflectometer (TDR) (Trase®, Soil Moisture, USA). Soil water storage *W* (mm) was calculated from soil water content measurements (volumetric water content) over the total soil depth.

Soil water was sampled below the vegetable root zone with soil moisture suction cups at a depth of 50 cm (at a suction of 33 kPa). Samples were analysed for nitrate N concentration and soluble and total N using standard methods (ISO/DIS 14255 and ISO 13878). The nitrate concentration results are expressed in mg/L N. For N isotope analysis nitrate was isolated from the soil water as ammonium sulphate using the micro diffusion method (Brooks and Stark, 1989). The isotopic composition of the samples was determined using a continuous flow isotope ratio mass spectrometer with an ANCA-SL preparation module (PDZ Europa Ltd., UK.). Nitrogen-15:nitrogen-14 ratios are reported in atom percent (atom %) ^{15}N excess, which is the value obtained by subtracting the ^{15}N concentration of the reference material — air N_2 (0.3663 atom % ^{15}N) from the measured sample concentration as follows (Kendall, 1998):

$$^{15}\text{N excess} = \text{measured } ^{15}\text{N concentration value–natural abundance [atom \%]} \quad (1)$$

The analytical precision of the isotopic measurements depends on the level of enrichment and was estimated to be ±0.002 atom %^{15}N for the samples below one atom %^{15}N and ±0.004 atom %^{15}N for samples above one atom %^{15}N, based on replicate measurements of the reference materials and samples. The following reference materials were used: IAEA 305-B (0.0503 atom %^{15}N), IAEA PLANT RM (1.187 atom %^{15}N) and IAEA-311 (2.05 atom %^{15}N). The N content of soil water was calculated from *W* (mm) and the nitrate concentration measured in the suction cups (mg/L), converted to kg/ha. Nitrate N losses were calculated from average nitrate concentration in the suction cups between two samplings and the amount of deep percolation (mm) between two samplings, converted to kg/ha, then summed over the growing period of the individual crop (Zupanc *et al.*, 2011).

For the final N uptake, plants were sampled at the end of each growing period for determination of dry matter yield and plant N uptake (i.e. N yield), calculated using the following equations (IAEA, Training Course Series No.14, 2001):

$$\text{Dry matter yield (kg/ha)} = \text{plant fresh mass(kg)} \times \frac{10\,000\,(\text{m}^2/\text{ha})}{\text{area harvested}\,(\text{m}^2)} \times \frac{\text{plant dry mass(kg)}}{\text{plant fresh mass(kg)}}, \quad (2)$$

$$\text{N yield (kg/ha)} = \text{dry matter yield (kg/ha)} \times \frac{\%\,\text{N}}{100} \quad (3)$$

Total N yield (kg/ha) was calculated by multiplying the dry matter yield of plant parts and their mean N concentration.

Nitrogen balance was calculated for the growing period of individual crops as the difference between N input and crop uptake on one side, and the difference in the N content of the soil water and the N loss on the other side. Nitrogen input (kg/ha) was the total N fertilizer added on the soil surface with either fertigation or broadcast application. Difference in the N content in soil water was calculated as the difference between nitrate concentration at beginning and at the end of the crop growing period.

Statistical analysis was conducted for a completely randomized design with three replications. Differences in nitrate concentration in soil water and in ^{15}N atom % excess were evaluated using repeated measure ANOVA for the dates when data for all treatments were available for a sampling event. Main effects were considered significant at $p \leq 0.05$. All statistical analyses were performed using SPSS 17.0 (SPSS, Inc., Chicago, USA).

RESULTS AND DISCUSSION

Due to the wet conditions in 2006, improved practices could not be tested. Nevertheless, there were large differences between the three treatments in terms of N losses through leaching, which were highest for the farmer's practice (Table 2) where as much as 160 kg N/ha was lost compared with only 36 kg N/ha for fertigation treatment. Relatively high N losses through leaching also occurred in the control treatment (116 kg N/ha). The high leaching was due to the high rainfall coupled with the large amount of irrigation being applied to both the farmer's practice and control treatments, as well to the high nitrate concentration in the suction cups (69, 50, and 23 mg/L for the farmer's practice, control and fertigation treatments, respectively). During the cabbage growing period nitrate N losses were negligible for all treatments as there was no deep drainage due to insufficient irrigation being applied (Table 2).

There were no statistical differences in N uptake between treatments for endive, an average of 65 kg N/ha being taken up by the crop (Table 2). On the other hand, N uptake for cabbage was statistically higher for the farmer's practice (246 kg/ha), extracting from the soil more N than was added by the farmer (Table 2). During the endive growing period, N balance was negative for all treatments as a consequence of the extremely unfavourable wet conditions and heavy deep drainage. For cabbage, N balance was negative for the farmer's practice as well as for the control treatment.

The highest ^{15}N enrichments of nitrate in soil water as well as the highest variability in ^{15}N were determined under the farmer's fertilization practice plots (Figure 1) in the wet part of the year (end of September–December for both 2006 and 2007), confirming the highest leaching in that treatment.

Split fertilizer application and applying the right amount of water at the correct time leads to better nutrient uptake and minimizes nitrate leaching compared with broadcast fertilization. This finding is consistent with findings of Logan (1993) and D'Arcy and Frost (2001)

TABLE 2. Rainfall, irrigation, ET_{crop}, estimated nitrate N leaching losses, N input, crop N uptake (n = 9) and N balance for fertigation, farmer's practice and control treatments at Sneberje, Slovenia

Parameter§	Endive 2006[1]			Cabbage 2007[1]		
	Fertigation	Farmer's practice	Control	Fertigation	Farmer's practice	Control
Rainfall	355	355	355	184	184	184
Irrigation	20	100	100	110	100	100
ET_{crop}	220	214	214	377	350	350
Estimated nitrate-N leaching losses	36	160	116	0	0	0
N input	79	80	0	200	200	0
Crop N uptake[2]	63[a]	69[a]	65[a]	169[b]	246[a]	84[c]
N balance	–20	–149	–181	31	–46	–84

1 Growing period; Endive = 10.08.–26.10.2006; Cabbage, 11.04.–26.6.2007

2 Different superscript letters (a,b,c) denote a statistically significant difference among treatments at $p < 0.05$, n = 9

§ Units of rainfall, irrigation, ET_{crop} (mm); units of N (kg/ha)

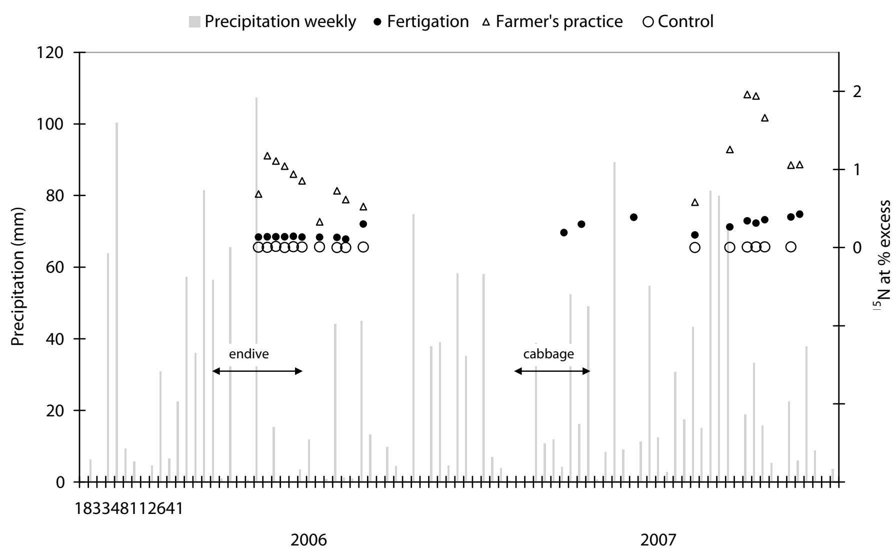


FIGURE 1. ^{15}N (atom % excess) in soil water collected with suction cups at 50 cm depth and weekly precipitation in Sneberje, Slovenia (2006–2007) for fertigation, farmer's practice and control treatments for endive (2006) and cabbage (2007).

and is the basis of 'best-management-practices' recommended to farmers in many countries (Morari, Lutago and Borin, 2004). Economic analysis combining agricultural and environmental measurements showed that the best management practice was not sufficient to satisfy the nitrate concentration constraint every year (Lacroix, Beaudoin and Makowski, 2005). Nevertheless, in water protection zones with severe restrictions on or prohibition of fertilizer applications, environmentally friendly techniques such as fertigation could be the solution for agricultural practices, enabling farmers to make profitable use of the land.

CONCLUSIONS

The results presented here provide guidelines for fertigation in the production of vegetables with a shorter growing period (i.e. lettuce and Brassicaceae), grown on areas where potentially high groundwater pollution is possible due to the soil texture and structure. With the help of nuclear techniques it was possible to identify environmentally more sustainable practices such as split application of nutrients compared with broadcast incorporating fertilization, which can and should be a practice of choice in water protection zones. Fertigation should therefore be considered as an environmentally friendly practice for vegetable production on or close to groundwater protection zones. Due to the anticipated higher energy and time inputs and lower yield outputs, environmentally friendly techniques should be supported by legislation, finance and education.

ACKNOWLEDGEMENTS

This project was supported by the Slovenian Research Agency applied research project L1-7097 Nitrate Migration in a Plant–Soil–Groundwater System, and by IAEA TC project SLO/5/002 Protecting Groundwater and Soil against Pollutants Using Nuclear Techniques.

The authors cordially thank farmer, Mr. Janez Janež for the use of the field and his cooperation in the farmer's part of the experiment.

REFERENCES

Almasri, M.N. & Kaluarachchi, J.J. 2005. Modular neural networks to predict the nitrate distribution in ground water using the on-ground nitrogen loading and recharge data. *Environ. Modell. Softw.*, 20: 851–871.

Brooks, P.D. & Stark, J.M. 1989. Diffusion method to prepare soil extracts for automated nitrogen-15 analysis. *Soil Sci. Soc. Am. J.*, 53: 1707–1711.

Burkart, M.R. & Stoner, J.D. 2008. Nitrogen in groundwater associated with agricultural systems. *In*: J.L. Hatfield & R.F. Follett, eds. *Nitrogen in the environment: Sources, problems, and management,* Second Edition, pp. 177–202. Amsterdam, Elsevier.

D'Arcy, B. & Frost, A. 2001. The role of best management practices in alleviating water quality problems associated with diffused pollution. *Sci. Total Environ.*, 265: 359–367.

Egboka, B.C.E. 1984. Nitrate contamination of shallow groundwaters in Ontario, Canada. *Sci. Tot. Environ*. 35: 53–70.

IAEA, 2001. Use of isotope and radiation methods in soil and water management and crop nutrition Training Course Series No. 14. Vienna.

ISO/DIN 14255. 1999. Soil quality — Determination of nitrate nitrogen, ammonium nitrogen and total soluble nitrogen in air-dry soils using calcium chloride solution as extractant (available at: http://www.iso.org/).

ISO 13878. 1998. Soil quality, determination of total nitrogen content by dry combustion ("elemental analysis"), (available at: http://www.iso.org/).

Kendall, C. 1998. Tracing nitrogen sources and cycling catchments. *In*: C. Kendall & J. McDonnell, eds. *Isotope tracers in catchment hydrology,* pp. 517–569. Amsterdam, Elsevier.

Lacroix, A., Beaudoin, N. & Makowski, D. 2005. Agricultural water nonpoint pollution control under uncertainty and climate variability. *Ecol. Econ*., 53: 115–127.

Logan, T.J. 1993. Agricultural best management practices for water pollution control: current issues. *Agr. Ecosyst. Environ*. 46: 223–231.

Morari, F., Lutago, E. & Borin, M. 2004. An integrated non-point source model-GIS system for selecting criteria of best management practices in the Po Valley, North Italy. *Agr. Ecosyst. Environ*., 102: 247–262.

Pandey, R.K, Maranville, J.W. & Chetima, M.M. 2000. Deficit irrigation and nitrogen effects on maize in a Sahelian environment: II. Shoot growth, nitrogen uptake and water extraction. *Agric. Water Manage.,* 46: 15–27.

Šturm, M., Kacjan-Maršič, N., Zupanc, V., Bračič-Železnik, B., Lojen, S. & Pintar, M. 2010. Effect of different fertilisation and irrigation practices on yield, nitrogen uptake and fertiliser use efficiency of white cabbage (*Brassica oleracea* var. capitata L.). S*ci. Hort. – Amsterdam,* 125: 103–109.

Zupanc, V., Šturm, M., Lojen, S., Kacjan-Maršič, N., Adu-Gyamfi, J., Bračič-Železnik, B., Urbanc, J. & Pintar, M. 2011. Nitrate leaching under vegetable field above a shallow aquifer in Slovenia. *Agric. Ecosyst. Environ*., 144: 167–174

Improving Irrigation Practice to Reduce Risk of Nitrogen Percolation into Deeper Aquifers in Vegetable Cultivation in Suburban Ha Noi, Viet Nam

D.N. Dang[1,*], N.H. Anh[2], T. T. Nguyen[3], A.M. Dang[3] and L.A. Ha[3]

ABSTRACT

This research demonstrates the advantages of drip irrigation with scheduling (DIS) over furrow irrigation (FI) for improving water use efficiency (WUE) and reducing the risk of potential nitrogen (N) contamination of groundwater in cabbage cultivation on alluvial soils of the Red River, North Viet Nam. Compared with FI, the DIS practice improved the irrigation WUE of the vegetable from 2.11 ± 0.35 to 5.23 ± 0.41 kg/m^3 during the autumn–winter (October–December), and from 2.15 ± 0.27 to 5.31 ± 0.35 kg/m^3 during the winter–spring (February–April) cropping seasons. Overall, DIS saved between 42 percent and 46 percent of water in comparison with FI during the autumn–winter and winter–spring seasons, respectively. It appears that with FI, ammonium (NH_4^+) percolates beyond the rooting depth of the crop, but in DIS it does not. Percolation could potentially cause groundwater contamination with NH_4^+. The delta nitrogen-15 ($\delta^{15}N$) values of ammonium in FI increased with increasing NH_4^+ concentration implying that there were at least two sources of N release, namely from inorganic fertilizer and from the manure applied. The $\delta^{15}N$ of the soil nitrate (NO_3^-) in FI was almost unchanged with increasing NO_3^- concentration, varying from 1‰ to 5‰, suggesting that NO_3^- was derived only from inorganic fertilizer. With DIS, soil NH_4^+ was found to be from the manure whereas NO_3^- was from inorganic fertilizers.

Key words: *cabbage, drip irrigation, scheduling, furrow irrigation, water use efficiency, nitrogen-15.*

INTRODUCTION

Vegetables are one of the most important foods of the Vietnamese people, particularly so in the city of Ha Noi where about 2600 tonnes (t) of various kinds of vegetable are consumed daily (DARD, 2011). Vegetables are currently produced on 3255 ha of land on the city's suburbs to supply 60 percent of the demand, the remaining comes from surrounding provinces. Among the 85 kinds of vegetables (spinach, cucumber, tomato, kohlrabi, beans, etc.), cabbage occupies around 20 percent of the production and trade on the market (DARD, 2011).

To have high levels of vegetable production, local farmers apply high rates of nitrogen (N), phosphorus (P), potassium (K) and urea fertilizers. For each cabbage season about 660 kg N–P–K and 300 kg urea are spread over one ha of land (DARD, 2009). Furrow irrigation (FI) is widely practised in Viet Nam for vegetable production and this is believed to be the cause of surface and groundwater quality deterioration. Surface and groundwater in the city of Ha Noi are currently polluted with N (Norrman *et al*., 2008). These authors have implicated as the reasons the overuse of inorganic fertilizers in agriculture and direct discharge of water waste from the city without further treatment. Recently, an annual report to the National Assembly from the Ministry of Natural Resources and Environment (MONRE) determined that a combination of inappropriate irrigation practices and heavy abstraction of groundwater for both irrigation and supplying the population were the main reasons for the deterioration in water quality (MONRE, 2009).

Against this background, it should be noted that studies on water and fertilizer use efficiency (WUE and FUE) in agronomy, and particularly in vegetable production in the country are still very limited. The aim of this study was therefore to compare the advantages of drip irrigation with scheduling (DIS) over the traditional furrow irrigation (FI) practice in cabbage production in suburban Ha Noi city for improving WUE, i.e. improving the profitability of production while preventing N fertilizer residues from percolating into the deeper soil profile and risking groundwater contamination. The results could assist agricultural managers in Viet Nam in developing measures for proper fertilizer use and appropriate irrigation practices for maintaining high crop productivity and protecting the environment.

EXPERIMENTAL DESIGN

The experiment was conducted in Nam Hong village, Dong Anh – a northeast district of Ha Noi city where vegetable production to supply the capital is the only activity of all farmers. Cabbage, a broad-leaf vegetable that needs more water than any other crop was supplied by the Petoseed Company (USA), the preferred variety by farmers of the village. The seasons and years of planting were autumn–winter (September–December) and winter–spring (February–April) of 2006, 2007 and 2008. Cabbage was transplanted on the ancient alluvial soil of the Red River, North Viet Nam. The texture of the soil in the rooting zone was 13 percent sand, 52 percent silt and 35 percent

1 Vietnam Atomic Energy Institute, 59 Ly ThuongKiet, Ha Noi, Viet Nam
2 Ha Noi Institute for Vegetable and Fruits Researches, Gia Lam, HaNoi, Viet Nam
3 Institute for Nuclear Science and Technology, 179 Hoang Quoc Viet, Ha Noi, Viet Nam
* E-mail address of corresponding author: dangducnhan50@gmail.com

L.K. Heng, K. Sakadevan, G. Dercon and M.L. Nguyen (eds), Proceedings — International Symposium on Managing Soils for Food Security and Climate Change Adaptation and Mitigation. Food and Agriculture Organization of the United Nations, Rome, 2014: 283–287

clay. Before planting the soil was treated with organic manure (chicken muck), and with N–P–K and urea fertilizers. The rate of manure application was 10 t/ha, while the inorganic fertilizers were applied to the crop four times during each season with a total of 360 kg urea, 510 kg superphosphate, and 270 kg potassium sulphate as follow: 20 percent of the total amount before planting, a second application of 25 percent of the total amount at the rooting period, a third application of 33 percent of the total amount when the canopy occupied 10 percent of the land, and last application of 12 percent during head formation.

The land area for the experiment was 450 m^2 and was split into two plots each of 225 m^2. The first plot was set up for traditional FI and the second for advanced DIS. Soil moisture was monitored using a neutron probe (PB-205, Fieldtech, Japan).

Irrigation scheduling and calculations

The time for watering in the DIS plot was established based on the assumption that the crop needed to be watered if the refill point (RP) was down to half of the available soil water content (ASWC), i.e.

$$RP = 0.5 \times AWSC \quad (1)$$

and

$$ASWC = FC - WP \quad (2)$$

where *FC* — field capacity, and *WP* — wilting point.

For the alluvial soil of the Red River, the *FC* and the *WP* of cabbage were experimentally determined (this study) to be 25 percent and 9 percent, respectively. The *ASWC* of the soil should be 16 percent. The *FC* and *WP* for a crop (mm) were estimated as the product of its root zone depth (*RZD*) in mm and *FC* expressed in percentage units, i.e.

$$FC\ (\text{mm}) = RZD\ (\text{mm}) \times FC\ (\text{percent}) \quad (3)$$

$$WP\ (\text{mm}) = RZD\ (\text{mm}) \times WP\ (\text{percent}) \quad (4)$$

The *RZD* of cabbage was assigned a value of 450 mm as recommended by Simonne, Duke and Haman (2007). Since there is usually no rain over the Ha Noi city area between September and April, the amount of water needed in the DIS could be estimated as:

$$I = RP + ET_c \quad (5)$$

where ET_c — crop evapotranspiration, calculated as:

$$ET_c = K_c \times ET_o \quad (6)$$

The crop coefficient (K_c) in Equation 6 for cabbage was taken from MAFF (2001). According to this publication, a value of Kc_{ini} = 0.7 was assigned for the period from planting to the time when the crop canopy covered 10 percent of the land; the Kc_{mid} = 1.05 was assigned for the period when 10–80 percent of the land was covered by the crop canopy and the Kc_{end} = 0.95 was used for the time between when 80 percent of the land was covered by the canopy and harvesting. The ET_o of the field was estimated using the Penman-Monteith model (Allen, 2000). The meteorological parameters of the locality were measured using a mini-meteorological station (Pro Vantage 2, USA).

With FI, the soil moisture was maintained at between 23 and 24 percent (i.e. almost at the FC point) from the rooting time until harvest, as was the local farming practice. To compare the irrigation WUE of the vegetables under the DIS and FI, the total amount of irrigated water (I) in both practices along with the vegetable yield were recorded. The amount of irrigated water was measured using a water meter. Vegetable yield was determined through two measures, namely the total biological (Y_{bio}) and edible (Y_{ed}) yields. The former was the total weight of vegetable harvested and included the weight of both green leaves and the head. The latter was the weight of the head only. This provided two values for WUE. Irrigation WUE was estimated according to Howell (2001).

$$WUE_{Bio} = \frac{Y_{Bio}}{I}\ (\text{kg/m}^3) \quad (7)$$

and

$$WUE_{ed} = \frac{Y_{ed}}{I}\ (\text{kg/m}^3) \quad (8)$$

In this paper only the results for WUE_{ed} are presented.

Soil analyses

To elucidate the possibility of ammonium (NH_4^+) and nitrate (NO_3^-) percolating into deeper soil profiles, concentrations of these substances between the soil surface and a depth of 100 cm were determined each 10 cm before planting and after harvesting. The soil cores were taken representatively from both fields using a corer (Eijkelkamp, The Netherlands). Ammonium and NO_3^- in soil samples (5 g air-dried) were extracted three times at room temperature for four hours using 2 molar (M) potassium chloride (KCl). The soil:solution ratio was 1:5 (w:w). The extracts were combined, filtered through 0.45 mm Millipore filter and then analysed using appropriate techniques (Bremner and Mulvaney, 1982). Ion-chromatography (Dionex 600, USA) was used to determine $NH_4^+$and NO_3^- .

Delta nitrogen-15 determination

The sources of N released in the soil were identified based on the d^{15}N values in the NH_4^+ and NO_3^- present in the soil samples (Mayer *et al*, 2002; Jin *et al*., 2004). A diffusion technique was used to trap NH_4^+ in the KCl extracts. To do this, a piece of Whatman filter (f10 mm) impregnated with potassium bisulphate ($KHSO_4$) (trap) and covered tightly on both sides with a thin Teflon film was allowed to float on the surface of the solution-extract. The extract was then alkalified with NaOH to pH 12 and the flask containing extract with the trap was immediately capped tightly and left for a week with occasional shaking. In this way, evolved NH_3 diffuses through the Teflon film and reacts quantitatively with the salt to form potassium ammonium sulphate [$K(NH_4)SO_4$]. This double salt decomposes with copper oxide (CuO) in the elemental analyser to convert NH_4^+into N_2 gas before entering the ion source of an isotope ratio mass spectrometer for the ^{15}N determination.

Nitrate in the extract was first reduced to NH_4^+ by the Devada reductive reagent magnesium oxide (MgO) under acidic conditions and an NH_4^+ trapping procedure was followed similar to that described above. The apparatus and procedure for the diffusion method used for δ^{15}N determinations were as described by Liu and Mulvaney (1992). The delta (δ^{15}N) is expressed as:

$$\delta^{15}N = \left(\frac{R_{^{15}N,sample}}{R_{^{15}N,std}} - 1\right) \times 1000 \quad (9)$$

where — abundance of ^{15}N isotope in the sample to be analysed, and — abundance of ^{15}N isotope in the standard used for determination of δ^{15}N. Atmospheric N was used as the standard for the δ^{15}N determination.

The δ^{15}N values of soil NH_4^+ and NO_3^- samples were determined using an isotope ratio mass spectrometer (IR MS, Micro mass, UK) with an uncertainty ($1\sigma \leq \pm 0.2‰$).

Table 1. Influence of irrigation practices on development parameters of cabbage

Irrigation practice	Growing span from planting to (days)			
	Rooting	Canopy covered 10% land	Head formation	Harvest
FI	10±2	41±3	50±2	92±3
DIS	10±2	40±3	51±3	92±3
F test (n=15)	NS*	NS	NS	NS

NS: no significant difference at $p<0.01$

Table 2. Influence of irrigation practices on biological parameters of cabbage

Irrigation practice	H_{pl} (cm)	D_c (cm)	No. green leaves	No. leaves in a head	H_h (cm)	D_h (cm)
DIS	30.2±5.7^b	66.2±3.8^b	37.0±4.6^a	37.2±3.5^a	13.8±2.1^a	22.0±3.6^a
FI	31.1±3.6^a	61.1±6.2^c	36.5±3.8^a	25.0±4.6^b	13.1±2.7^b	21.8±3.5^a
F test (n=15)	23.4**	59.18**	NS	170.8**	4.76*	NS

Notes: H_{pl} — plant height; D_c — canopy diameter; H_h — head height; and D_h — the head diameter. Figures marked with the same letter for the DIS and FI practices imply no significant difference (ns) by F-test, but those with different letters imply that there is a difference between the two figures at significance levels of 5 percent and 1 percent respectively, with one and two asterisks.

TABLE 3. Influence of irrigation practices on the productivity and WUE_{ed} of cabbage

Treatment	A–W season (2006–2008)				W–S season (2006–2008)			
	Density (plants/m^2)	Y_{ed} (t/ha)	Irrigated water, I (m^3/ha)	WUE_{ed} (kg/m^3)	Density (plants/m)	Y_{ed} (t/ha)	Irrigated water, I (m^3/ha)	WUE_{ed} (kg/m^3)
Furrow irrigation	2.6±0.4	31. 7±0.5	12.7×10^3	2.11±0.35	2.7±0.3	25.8±0.7	12.5x10^3	2.15±0.27
Drip irrigation	2.5±0.4	39.2 ±0.3	7.5×10^3	5.23±0.41	2.5±0.4	36.1±0.3	6.8×10^3	5.31±0.35

RESULTS AND DISCUSSION

Influence of irrigation practices on the development of cabbage

Tables 1 and 2 show the influence of the DIS and traditional FI practices on the development and biological parameters of cabbage (*Petoseed* var.). Results are the mean values and standard deviations for each parameter obtained for five harvesting seasons: three for autumn–winter (A–W, October–December) and two for winter–spring (W–S, January–March) during the period 2006–2008.

As seen from Table 1, DIS did not affect the growing span of the vegetable, the time span from planting to harvesting of the crop being almost the same in the both DIS and FI and the crop could be harvested after 90–95 d. However, DIS did impact on the major biological parameters of cabbage (Table 2). Usually, farmers believe that a high soil moisture level makes nutrients more available to crops, and therefore that furrow irrigation should be a better practice to supply more nutrients to crops leading to higher productivity. In fact, as shown (Table 2), high moisture (23–24 percent in the FI) reduced the number of leaves in the head (edible leaves) although the head diameter was the same for the crop under both irrigation practices. This means that under DIS the leaves in the cabbage head were more compactly arranged than under FI, and as a consequence the productivity of the vegetable under DIS would be higher than under FI.

Influence of irrigation practices on the productivity of cabbage

Table 3 shows the influence of the different irrigation practices on the productivity of cabbage produced in the A–W and W–S seasons along with WUE_{ed} under the two irrigation practices.

Although the density of plants was the same with both irrigation practices (2.5 and 2.6 plants/m^2), the edible yield of the vegetable under DIS was 24 and 40 percent higher than that under the traditional FI for A–W and W–S seasons. At the same time, the DIS practice led to 41 and 46 percent saving water used for irrigation during A–W and W–S seasons (Table 3). The amount of irrigated water used in the W–S season was somewhat less than in the A–W season because sometimes during the W–S season drizzle made the soil moist and irrigation was managed infrequently. WUE_{ed} was estimated based on the Y_{ed} and I (Table 3). For the A–W season, the WUE_{ed} of cabbage improved from 2.11 kg/m^3 under FI to 5.23 kg/m^3 under the DIS, in the W–S season the corresponding figures were 2.15 kg/m^3 and 5.31 kg/m^3. These differences probably arose because the number of edible leaves in the head under DIS was almost 50 percent more than under the FI practice (Table 2). The lower productivity of vegetable under FI could also be explained by the fact that the soil under FI became too wet since soil moisture levels were almost at an FC of 25 percent, thereby preventing the cabbage to develop its secondary roots for more effective absorption of water and nutrition. Also, in some cases under wet conditions a number of diseases may occur within the root system like *Phytophthora* root rot of chile pepper grown under FI (Xie *et al.,* 1999).

From these results, one can estimate the amount of water that could be saved in cabbage production on 20 percent of the 3255 ha used for cultivation in the city of Ha Noi if DIS technology were applied. The figure was around 3.55 x 10^6 m^3 each cropping season. Additionally, using DIS technology local famers could gain more profit from cabbage production because of extra yields as much as 4 900 and 6 700 t, worth US\$1.2 and US\$1.6 million respectively for the A–W and W–S seasons, assuming the market price was US cents 0.25/kg.

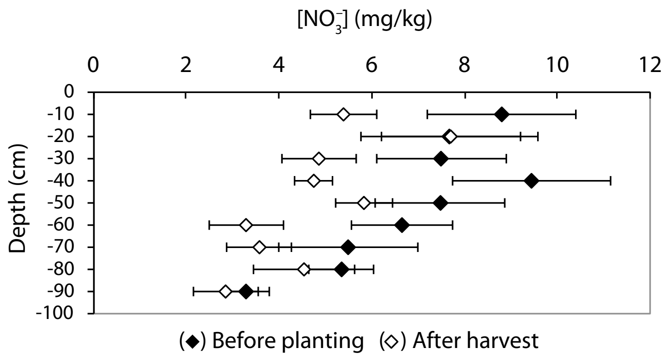


FIGURE 1. Variation of nitrate concentration (±1σ) along the soil profile with FI of cabbage.

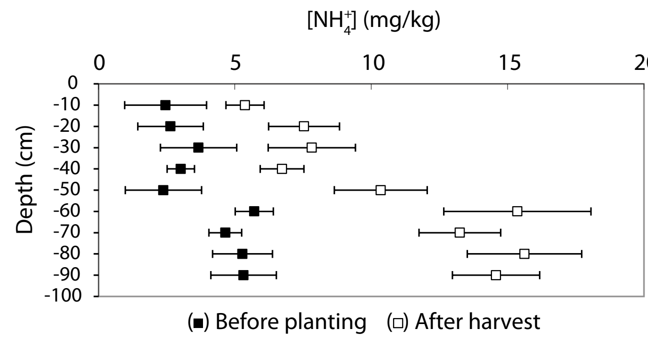


FIGURE 2. Variation of ammonium concentration (±1σ) along the soil profile with FI of cabbage.

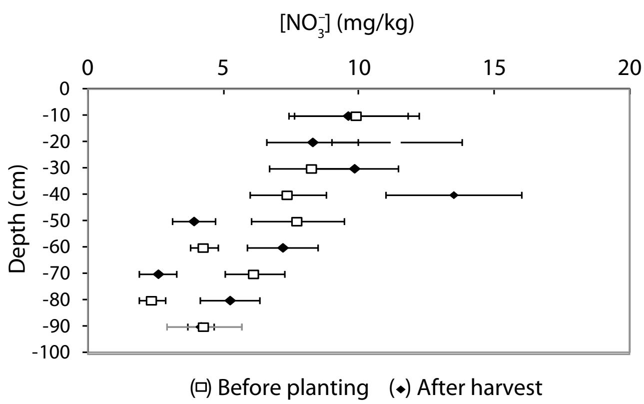


FIGURE 3. Variation of nitrate concentration (±1σ) along soil profile with DIS of cabbage.

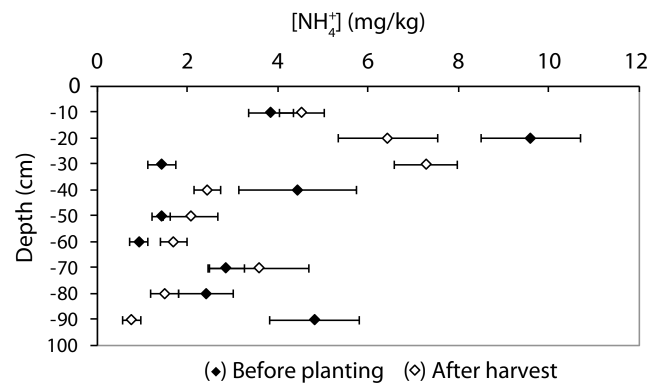


FIGURE 4. Variation of ammonium concentration (±1σ) along soil profile with DIS of cabbage.

Percolation of nitrogen fertilizer beyond crop rooting depth under different irrigation practices

Figures 1 and 2 depict the variation in NO_3^- and NH_4^+ concentrations along the soil profile with FI, while Figures 3 and 4 illustrate the variations with DIS. The data covered all five harvests between 2006 and 2008.

Figures 1 and 3 indicate that NO_3^- did not percolate into the deeper soil layers under either irrigation practice, with concentrations ranging from 2 to10 mg/kg soil. The highest NO_3^- concentration was found in the surface soil, but levels decreased with the soil depth. In contrast to NO_3^-, NH_4^+ under the FI seemed to percolate into the deeper soil profile (Figure 2), but not to the same extent in the DIS (Figure 3). Under FI, at a depth of 80 cm from the surface, the soil NH_4^+ concentration before planting was found to be 5.0 ± 1.0 mg/kg and it increased to 15.7 ± 1.0 mg/kg after harvest, almost three times higher than the NH_4^+ concentration in the surface soil. These findings suggest that the environment in the soil under the two irrigation practices as well as the sources of NO_3^- and NH_4^+ in the soil were different. Under FI the soil environment probably was reductive as the moisture level was high at all times (i.e. around an FC of 25 percent), which is not ideal for enabling air to diffuse into the soil and NH_4^+ to be oxidized. Under DIS, the environment in the soil was most probably oxidative since the soil moisture was low (10–15 percent), facilitating air diffusion and thereby oxidation of NH_4^+ in the rooting zone. The balance between soil and vegetable N (results not show here) and the total amount of N-nutrient applied initially to the crop showed that most N was volatilized, making the fertilizer use efficiency of the crop very low (between 20–30 percent only).

Sources of N-contaminant in soil under different irrigation practices

Figures 5 and 6 depict the relationship between ^{15}N composition ($\delta^{15}N$, ‰) and NO_3^- and NH_4^+ concentrations in soil under the FI and DIS practices, respectively. As seen from Figure 5 the composition of ^{15}N in soil NO_3^- under FI ranged from 3 to 7‰ and there was no clear trend for the relationship between $\delta^{15}N$ (nitrate) and concentration. This implies that the soil NO_3^- originated from the inorganic fertilizer applied because both the urea and the N in the N-P-K were synthesized from the air (Mayer *et al.*, 2002). In contrast to NO_3^-, the ^{15}N composition in NH_4^+ increased with its increasing concentration of NH_4^+ in soil (Figure 5). This suggests that NH_4^+ in the soil was from at least two different sources, probably from the organic manure and inorganic fertilizer (Mayer *et al.,* 2002). Assuming that soil NH_4^+ concentrations under FI followed an additive model, the contribution of each individual source was estimated to be 50 percent at an NH_4^+ concentration of 15 mg/kg and an assumed ^{15}N composition in inorganic fertilizer and manure to be respectively 5‰ and 25‰ (Mayer *et al.,* 2002).

Under DIS, the ^{15}N composition in NH_4^+ declined with increasing soil NH_4^+ concentration (Figure 6). In this case, it appears that the manure applied was the major source of soil NH_4^+ as ammonification of organic matter leads to depletion of the heavy isotope of N (Mayer *et al.,* 2002). However, the ^{15}N composition in NO_3^- under DIS did not vary with concentration, and was within 5‰–7‰ indicating that the soil NO_3^- under DIS was from the inorganic fertilizer applied, like that observed under FI.

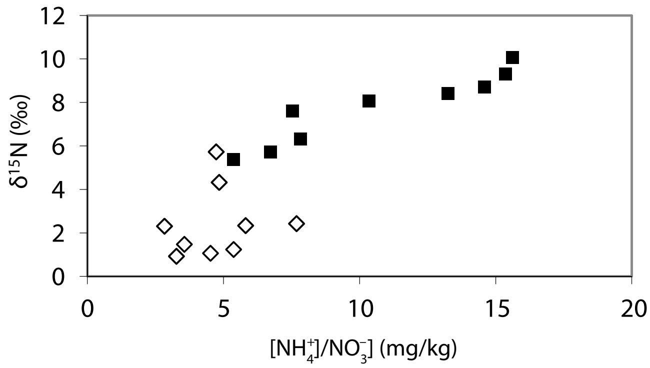


FIGURE 5. Relationship between ^{15}N composition and nitrate (◊) and ammonium (■) concentrations in soil under FI of cabbage.

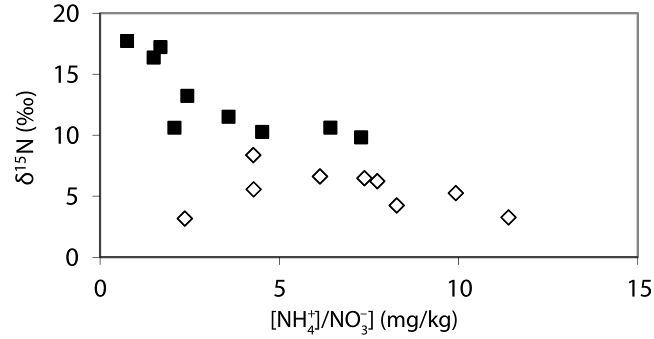


FIGURE 6. Relationship between ^{15}N composition and nitrate (◊) and ammonium (■) concentrations under DIS of cabbage.

CONCLUSIONS

Drip irrigation with scheduling improved the WUE of cabbage produced on the ancient alluvial soil of the Red River in suburban Ha Noi city, Viet Nam by up to 150 percent compared with the traditional FI practice in both autumn–winter and winter–summer seasons. Additionally, local farmers could gain an extra-profit by applying the former irrigation practice $US2.9 million per year from cabbage production on 651 ha of their land. Drip irrigation reduced the risk of groundwater contamination by N originating from fertilizers. The soil nitrate under both irrigation practices was from inorganic fertilizers (N-P-K, and urea), while ammonium under FI was from both inorganic and organic fertilizers; however, under the DIS it originated mainly from organic manure.

Proper use of N fertilizers and management of irrigation water in agriculture should be given particular attention in Viet Nam to maintain highly productive crops and to minimize the risk of water resources deterioration because of agrochemical residues percolating into groundwater.

ACKNOWLEDGEMENTS

The financial support from the Ministry of Science and Technology (Viet Nam) under the Research Theme encoded BO/06/04-02 is acknowledged. The authors would like to express their thanks to farmer Nguyen Van Truong and his wife Nguyen Thi Mai for taking care within insect pest control on the cabbage field during the entire period of the experiment.

REFERENCES

Allen, R.G. 2000.Using the FAO-56 dual crop coefficient method over an irrigated region as part of an evapotranspiration intercomparison study. *J. Hydrol*., 229: 27–41.

Bremner, J.M. & Mulvaney, C.S. 1982.Nitrogen-total. *In* A.L. Page, R.H. Millar & D.R. Keeney, eds. *Methods of soil analysis. Part II. Chemical & Microbiological Properties,* 2nd Edition, pp. 592–622. Agronomy Monograph 9, Madison, WI, ASA and SSSA.

Department of Agriculture and Rural Development of the Ha Noi City. 2009. *Fertilizers use in vegetable production in Ha Noi.* Annual Report to the People's Council of the Ha Noi City (in Vietnamese).

Department of Agriculture and Rural Development of the Ha Noi City. 2011. *Vegetable production and trade in the markets of the Ha Noi City.* Annual Report to the People's Council of the Ha Noi City (in Vietnamese).

Howell, T.A. 2001.Enhancing water use efficiency in irrigated agriculture. *Agron. J.*, 93: 281–289.

Jin, J-F., Chen, Y-X., Wang, F. & Ogura, N. 2004. Detection nitrate sources in urban groundwater by isotopic and chemical indicators, Hangzhou city. *China Environ. Geology,* 45: 1017–1024.

Liu, Y.P. & Mulvaney, R.L. 1992. Use of diffusion and automated nitrogen-15 analysis of soil extracts. *Soil Sci. Soc. Am. J.*, 55: 1016–1020.

Mayer, B., Boyer, E., Goodale, C., Jaworski, N., van Breemmen, N., Howarth, R. W., Seitzinger, S., Billen, G., Lajtha, K., Nadelhoffer, K., van Dam, D., Hetling, L., Norsal, M. & Paustian, K. 2002. Sources of nitrate in river draining sixteen water sheds in the northeastern U.S. Isotopic constraints. *Biogeochem.*, 57/58: 171–179.

Ministry of Agriculture, Food and Fisheries, British Columbia. 2001. *Crop coefficients for use in irrigation scheduling.* pp. 6. Water Conservation Factsheet No.577.100–5.

Ministry of Natural Resources and Environment. 2009. *Report of the Minister to a National Assembly Congress*, Ha Noi (in Vietnamese).

Norrman, J., Sparrenbom, C.J., Dang, D.N., Harms-Ringdahl, P., Jack, G., Rosqvist, H., Pham, Q.N. & Nguyen V.H. 2008. Arsenic mobilization in a new well field for drinking water production along the Red River, Nam Du, Ha Noi. *App. Geochem*., 23: 3127–3142.

Simonne, E.H., Duke, M.D. & Haman, D.Z. 2007. Principles and practices of irrigation management for vegetables. Factsheet No. EA260. (http://edis.ifas.ufl.edu/ pdffiles/CV/CV10700.pdf).

Xie, J.H., Cardenas, E.S., Sammis, T.W., Wall, M.M., Lindsey, D.L. & Murrey, M.W. 1999. Effect of irrigation methods on chile pepper yield and *Phytophthora* root rot incidence. *Agric. Water Manage.,* 42: 127–142.

Improving Yield and Water Use Efficiency of Wheat (*Triticum aestivum* L.) by Regulating Plant-Available Water during Crop Development under Semi-arid Conditions in Pakistan

K. Mahmood[1,*], W. Ishaque[1] and L.K. Heng[2]

ABSTRACT

Scarcity of irrigation water in Pakistan warrants adoption of appropriate practices for maximizing crop water use efficiency that at present is far lower compared with other countries. The objective of this research was to enhance water use efficiency (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 four crop seasons (2008–2012). 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 quite reliable for predictions of crop development (canopy cover and in-season biomass), crop yield, soil water dynamics and thus water productivity under different irrigation regimes. Since water saving through deficit irrigation would allow irrigation of additional crop area, the AquaCrop model can be a useful tool for assessing crop requirements and devising irrigation strategies to enhance water productivity under different scenarios.

Key words: *regulated deficit irrigation, wheat, water use efficiency, AquaCrop model, crop development and yield, soil water.*

INTRODUCTION

Pakistan has an arid/semi-arid climate in most of its area where annual pan evaporation (1 600 mm) exceeds rainfall by four to five-fold. Consequently, crop production relies heavily on irrigation, about 60 percent of which is contributed from the Indus river system (Iqbal and Munir, 2006). The main source of irrigation water from canals is insufficient to meet crop requirements particularly during the winter season. This water deficiency is met mostly with poor quality groundwater leading to alarming depletion of aquifers and also soil degradation due salinization of productive land. Hence, better irrigation water management is of prime importance to increase crop water use efficiency, enhance yield, reduce soil degradation and ensure food security under changing climate scenarios.

The limited scope for expansion of the cultivated area for crop production and water scarcity necessitate practical measures to maximize crop water use efficiency (WUE) while minimizing any adverse impact on yields, soil and environment. Higher WUE in agriculture can be achieved by maximizing crop water productivity using efficient irrigation techniques such as drip and deficit irrigation. The important practice of deficit irrigation to achieve higher water productivity and reducing irrigation water use has not received sufficient attention in research (Fereres and Soriano, 2007). Geerts and Raes (2009) reviewed selected research from around the world covering a range of crops and summarized the advantages and disadvantages of deficit irrigation. 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. Applying deficit irrigation and other irrigation management technologies based on quantitative estimation of irrigation demand has been demonstrated successfully and is now widely used in Andalucia, Spain (Fereres, Orgaz and Gonzalez-Dugo, 2011).

Deficit irrigation requires accurate estimation of potential crop evapotranspiration (ETc), which is difficult to compute accurately without computer models which can predict crop growth and evapotranspiration partitioning into soil evaporation and transpiration components (Gallardo *et al*., 1996). The recently developed FAO AquaCrop model has the ability to separate deep percolation, evaporation and transpiration components of the total water budget during a crop growing season. This model simulates crop yields as a function of water consumption under stored soil water/rain-fed, deficit, and full irrigation conditions (Steduto *et al*., 2009a; Farahani, Izzi and Oweis, 2009) and is an important tool for estimating crop water productivity under different irrigation management strategies for improving WUE in agriculture (Heng *et al*., 2009; Steduto *et al*., 2009b).

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.

MATERIALS AND METHODS

Study area

This research 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 climate of the area is

1 Nuclear Institute for Agriculture and Biology (NIAB), Faisalabad, Pakistan
2 International Atomic Energy Agency (IAEA), Vienna, Austria
* E-mail address of corresponding author: kmahmoodniab@yahoo.com

L.K. Heng, K. Sakadevan, G. Dercon and M.L. Nguyen (eds), Proceedings — International Symposium on Managing Soils for Food Security and Climate Change Adaptation and Mitigation. Food and Agriculture Organization of the United Nations, Rome, 2014: 289–296

semi-arid, with average annual rainfall of about 350 mm, of which approximately 80 percent occurs during the monsoon season from July to September. The area also receives winter showers of less intensity from December to February during the wheat growing season (November–April). Mean daily minimum temperatures range from 15 to 31°C, and maximum temperature from 32 to 48°C. Soil of the study site is *Typic Ustochrepts* with loam texture, deep, alkaline calcareous in nature, poor in organic matter (< 1 percent) and total soil nitrogen (< 0.05 percent). Selected physical properties of the soil (0–95 cm) are given in Table 1.

Experimental design and crop management

A series of field experiments was conducted for four consecutive crop seasons during 2008–2012, to determine the yield and WUE of wheat (*Triticum aestivum* L.) under varying irrigation water applications in a randomized complete block design with four replicates. Similar cultural practices were followed during different crop years. Pre-sowing irrigation of (≈75 mm) was applied uniformly to all plots. Seed at 125 kg/ha (90 percent germination) was sown with a drill. Nitrogen as urea at 125 kg/ha was applied in two splits, half at sowing and half top-dressed at the early tillering stage (1^{st} irrigation). Phosphorus was applied as basal dose at 250 kg/ha in the form of di-ammonium phosphate (DAP, 46 percent P_2O_5) at sowing time.

In the initial trial, wheat was grown with different irrigation levels, i.e. rain-fed (O–O–O–O) and 100 percent ETc (I–I–I–I) in 2008–2009. Subsequently, during the years 2009–2010 and 2010–2011, the irrigation treatments included: 100 percent ETc in four irrigations at four growth stages of the crop (I–I–I–I) and one irrigation missed at each of these stages, i.e. crown root initiation/tillering, booting, flowering and grain formation stages, respectively, to determine the critical crop growth stages. Tillering and flowering were identified as more sensitive crop growth stages to irrigation application with higher reductions (> 10 percent) in biomass and grain yield (data not shown). Based on the these results, regulated deficit irrigation treatments at comparatively less sensitive stages (booting and grain filling) were applied in 2011–2012, which included: 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).

Crop evapotranspiration (ETc) and irrigation

Crop evapotranspiration (ETc) was calculated using the water balance approach which considers irrigation, rainfall, soil water depletion, deep drainage and runoff. To assess the changes in soil water content in the root zone during crop growth, water status at different soil depths was measured using a neutron moisture meter (NMM) calibrated on-site. Calibration equations relating the count ratio (CR) to the volumetric soil water content (θ) were obtained using a non-weighted, least squares regression technique (Table 2). Water contents of the top 15 cm were also determined gravimetrically.

Soil water contents at sowing and harvest of the crop were determined gravimetrically at 15 cm increments over 0–95 cm of the soil profile. Irrigation water, collected in a tank (32 m^3 [4 x 4 x 2 m]), was pumped through a pipe system and the amount applied to each treatment sub-plot was measured using a flow meter connected between the pump and delivery pipe line. This practice ensured full and uniform water coverage/distribution in the sub-plots and no surface runoff occurred at any time during the crop growth. Irrigation treatments were started immediately after sowing by withholding or applying the irrigation for different treatments, as and when required.

Weather data including daily maximum and minimum air temperatures (°C), humidity, wind speed and daily hours of sunshine (h) were obtained from the University of Agriculture, Faisalabad, while rainfall (mm) was measured at the experimental site. The reference crop evapotranspiration (ETo) was estimated using the ETo Calculator (Version 3.1 http://www.fao.org/nr/water/eto.html) developed by FAO's Land and Water Division, Rome, Italy. Reference crop evapotranspiration, maximum and minimum temperature files were further used in the AquaCrop model. The crop data file for the AquaCrop model contained crop-specific parameters related to development (initial canopy cover, canopy development, flowering and yield formation, and root depth), production (water productivity, harvest index) and biomass stress (soil fertility, soil salinity, soil fertility/salinity). The crop development stages were defined when 50 percent of the plants showed visual signs of the stage being considered. For this purpose, 10 plants from each treatment and replicate were tagged after emergence of the crop 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) maturity.

In-season aboveground biomass was determined at different growth stages by clipping the plants at the soil surface within a randomly selected area (1 m × 1 m) in each treatment plot. The corresponding canopy cover development (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. The crop was harvested at maturity and total biomass, grain yield and harvest index were determined. From the biomass, grain yield and soil water balance, biomass-based and grain-based WUE (i.e., WUEb and WUEg, respectively) were calculated.

Soil, water and irrigation files were prepared and measured/estimated crop parameters were inserted in the model. 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.

The model was calibrated with the non-stressed treatment data from 2008–2009. To check the accuracy of simulations, the model

TABLE 1. Selected physical properties of soil of the experimental field

Depth (cm)	Texture	Bulk Density (g/cm^3)	θ FC (m^3/m^3)	θ WP (m^3/m^3)	Ksat (mm/hr)
0–15	Loam	1.56	29.8	13.1	4.50
15–35	Loam	1.39	27.4	12.6	5.53
35–55	Loam	1.37	27.0	12.6	5.89
55–75	Loam	1.43	24.5	12.0	8.12
75–95	Loam	1.46	22.8	11.3	10.40

θ — volumetric water; FC — field capacity; WP — wilting point; Ksat — saturated hydraulic conductivity

TABLE 2. Calibration equations of NMM for different soil depths

Depth (cm)	Equation	R^2
0–15	θ = 0.578 CR – 0.242	0.90
15–35	θ = 0.465 CR – 0.189	0.92
35–55	θ = 0.397 CR – 0.139	0.90
55–75	θ = 0.280 CR – 0.038	0.83
75–95	θ = 0.265 CR – 0.020	0.80

AquaCrop calibration and validation

was run with data recorded for irrigated and rain-fed treatments during the years 2009–2010 and 2010–2011 and for all the treatments in the year 2011–2012. During this process, available data on grain yield, total crop biomass and maximum canopy cover were compared with simulated values. Simulation performance was evaluated by calculating different statistic indices like root mean square error (RMSE) (Wallach and Goffinet, 1989) and modelling efficiency (EF) in all the treatments. Time-course simulations of crop biomass and canopy cover were assessed by an index of agreement (d) (Willmott, 1981) that is an aggregate overall indicator. These parameters were calculated as follows:

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

$$EF = 1 - \frac{\sum_{i=1}^{n}(M_i - S_i)^2}{\sum_{i=1}^{n}\left(M_i - \bar{M}\right)^2}$$

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

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.

RESULTS AND DISCUSSION

Climatic parameters

Patterns of rainfall and air temperature at the study site over the last ten years are shown in Figure 1. Normally May is the driest month of the year with an average relative humidity 30 percent that may rise to over 70 percent during monsoon (July and August) and then decreases gradually in October and November. Due to winter rains, the weather becomes more humid with maximum mean relative humidity (> 70 percent) recorded for the month of January. The maximum temperature in summer may occasionally reach up to 50°C in June with average maximum and minimum temperatures of 45°C and 28°C, respectively. Average daily evaporation varies from 2 mm in January to a maximum average of 11.4 mm in May and June with annual excess of pan evaporation in the range of about 1 600 mm over rainfall. During the wheat growing season (November–April), temperature may, at times, fall below freezing point in December and January with an average minimum temperature of ≈ 2°C. Based on the 10-year mean, approximately 72 mm rainfall occurs in the wheat

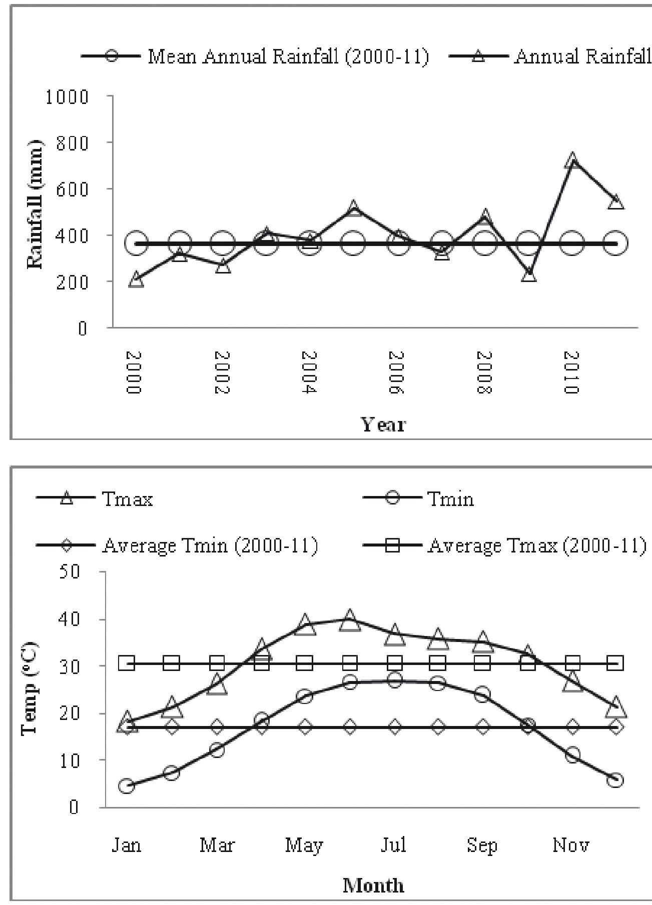


FIGURE 1. Patterns of rainfall and air temperature at the study site (2000–2011).

growing season. However, during the study period, the highest rainfall was recorded in 2008–2009 (65 mm) and the lowest in 2011–2012 (13 mm). Most of the rainfall during the 2008–2009 cropping season was in early November (25 mm) just before sowing and mid-April (20 mm), making only about 20 mm utilized by the crop. Similarly, the contribution of rainfall to plant consumed water between 2009 and 2012 was < 40 mm.

Yield and water use efficiency (measured)

Aboveground biomass and grain yield of wheat were significantly higher in irrigated than the rain-fed treatment in all four years (Table 3). Under rain-fed conditions, comparable values for biomass, grain yield, and HI (harvest index) were recorded in all the study years. Average biomass, 6.08 t/ha and grain yield 2.0 t/ha gave a harvest index of 33 percent. However, significantly lower WUEb and WUEg values were obtained in the 2009–2010 and 2011–2012 seasons due to poor rainfall in early April when the crop was near to maturity. These rainfall events affected the total water balance but did not contribute to increases in total biomass or grain yield. Water use efficiency was significantly higher under rain-fed than irrigated conditions but this was related to drastic decreases in biomass and grain yields of the rain-fed crop (Table 3). Average reductions in WUEb and WUEg under irrigated condition were, respectively, ≈ 16 percent and 8 percent compared with those under rain-fed condition.

Biomass ranged from about 12–15.3 t/ha (average 14.2 t/ha) and grain yield 4.68–5.70 t/ha (average 5.3 t/ha) in irrigated treatments during the four-year study (Table 3). Under regulated deficit

TABLE 3. Yield and water use efficiency of wheat grown under different irrigation levels during four crop years (2008–2012). Values are means of four replicates

Crop	Treatment	Biomass (t/ha)	Grain Yield (t/ha)	HI (%)	WUEb (kg/ha·mm^{-1})	WUEg (kg·ha^{-1}·mm^{-1})
2008–09	I–I–I–I	13.51	5.10	36.67	53.85	19.72
2009–10	Rain-fed	5.83	2.10	36.02	39.58	14.30
	I–I–I–I	11.98	4.68	39.07	33.60	13.05
2010–11	Rain-fed	6.07	1.89	31.13	55.20	17.20
	I–I–I–I	15.30	5.70	37.30	48.30	18.00
2011–12	Rain-fed	6.53b	1.97b	30.00b	45.20a	13.70b
	I–I–I–I	15.03a*	5.46a	36.70a	41.70ab	15.20a
	I–0.5I–I–I	14.20a	5.23a	36.70a	41.80ab	15.40a
	I–I–I–0.5I	14.36a	5.30a	37.00a	40.50b	15.00ab
	1–0.5I–I–0.5I	14.10a	5.13a	36.70a	42.20ab	15.30a

*Values followed by same letter in a column are not significantly different (crop 2011–2012)

irrigation, preliminary results showed insignificant differences among the treatments for biomass, grain yield and harvest index. However, the lowest WUEb (40.5 kg·ha^{-1}·mm^{-1}) was obtained when irrigation was reduced at the grain filling stage (I–I–I–0.5I). In comparison with other treatments, similar WUEg values ≈ 15.3–15.4 kg·ha^{-1}·mm^{-1} were found when irrigation was reduced at the booting stage (I–0.5I–I–I) or at both the booting and grain filling stages (1–0.5I–I–0.5I).

AquaCrop simulations

Model calibration

The AquaCrop model was calibrated against measured data for in-season biomass, canopy cover, biomass at harvest and grain yield under the non-stressed irrigated treatment for the year 2008–2009. The calibration procedure involved adjustments in crop phenology including plant population, days taken by the crop to emergence, full canopy cover, flowering, senescence and harvest. During calibration, in-season biomass and canopy cover predicted with AquaCrop closely followed the observed values with a reasonable root mean square error (RMSE), index of agreement (d) and modelling efficiency (E). Low RMSE values (0.47 for biomass and 9.0 for CC) along with high d and E (closer to 1) demonstrate the adequacy of model calibration (Figure 2) for simulating in-season biomass and canopy cover.

Soil water and water balance

Fluctuations in volumetric soil water measured with neutron probe (NMM) for different depths for the rainfed and fully irrigated treatments for the 2011–2012 season are given in Figure 3. No appreciable water movement in any cropping year was observed beyond 75 cm of soil depth under irrigation treatment, indicating that all irrigation water applied was either lost in the form of soil evaporation or transpired by the crop. The model predictions were quite satisfactory for simulating soil water content in the soil depths studied with a smaller range in RMSE (2.58–3.74) and d (0.94–0.84). Coefficients of regression (R^2) also indicated reasonable correlations between simulated and observed water contents ranging from 0.89 to 0.76. However, model predictions for soil water contents were relatively higher for different soil depths compared with observed values in all the years. The spatial variability within the individual soil columns may cause some differences in the measured values especially in the water stress treatments (Heng *et al.*, 2009). In the present study, overall simulated and measured soil water contents were closely correlated for the four-year data (Figure 3).

Total soil water balance based on the water budget approach (Figure 4) showed some irrigation water loss by the model in the form of drainage under irrigated treatment during all the cropping years. As a result, the model under-predicted the total water consumed in the form of evaporation and transpiration by the crop. On the other hand, no deep percolation losses were observed beyond the root zone (Figure 3). The accuracy of model prediction to simulate total water consumed by the crop was improved (R^2 = 0.90) when the simulated drainage component was added to the total predicted evaporation and transpiration components of water balance (Figure 4).

Yield and water use efficiency (simulated)

The deviations of simulated values for biomass and grain yield from measured values are expressed as percentages of measured values (Table 4) and show reasonable predictions by the model. The deviations between measured and simulated biomass at harvest (1.26 percent) and grain yield (0.98 percent) were less than 2 percent during calibration. For the 2009–2010 crop, values of in-season biomass and root growth (depth) predicted by AquaCrop were higher with RMSE 1.46 (Figure 2) and higher differences in end-season biomass, i.e. 19.9 percent for rain-fed and 7.35 percent for irrigated conditions. The differences require reassessment of the validity of the model.

The RMSE, d and E values for irrigated (I–I–I–I) and rain-fed (O–O–O–O) treatments (Figure 2) showed that overall prediction of crop growth parameters were simulated well for irrigated treatments. However, some over-estimations of biomass and canopy growth with higher deviations in final biomass and grain yields were observed under rain-fed treatment in the years 2009–2011 (Table 4). A similar trend was observed for this treatment in 2011–2012. This over-estimation was due to higher predicted in-season biomass and canopy growth.

For different regulated (deficit) irrigation treatments during 2011–2012, the model predicted in-season biomass accurately in all the treatments with mean RMSE, d and E values of 0.64, 0.98 and 0.97, respectively. These predictions were comparatively less accurate for canopy growth, with higher RMSE = 12.45 when irrigation was reduced at grain formation (I–I–I–0.5I) and lower RMSE = 6.32 at half irrigation at both booting and grain formation stages (I–0.5I–

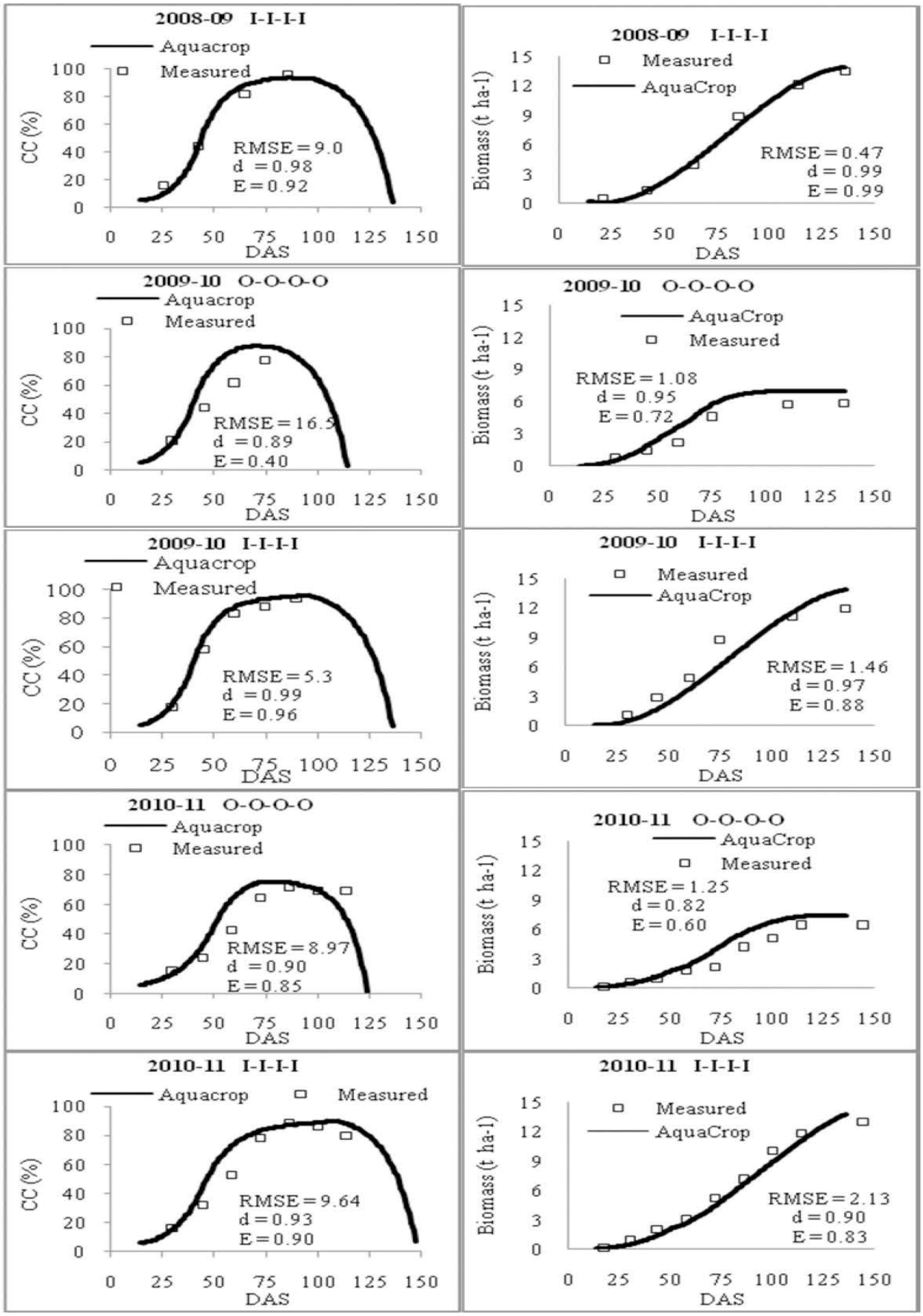


FIGURE 2. Simulated (AquaCrop) and measured values of in-season biomass and canopy cover along with statistical indicators of RMSE, d and E showing adequacy of model fitting during calibration (2008–2009) and validation (2009–2010 and 2010–2011) under irrigated (I–I–I–I) and rain-fed (O–O–O–O) conditions.

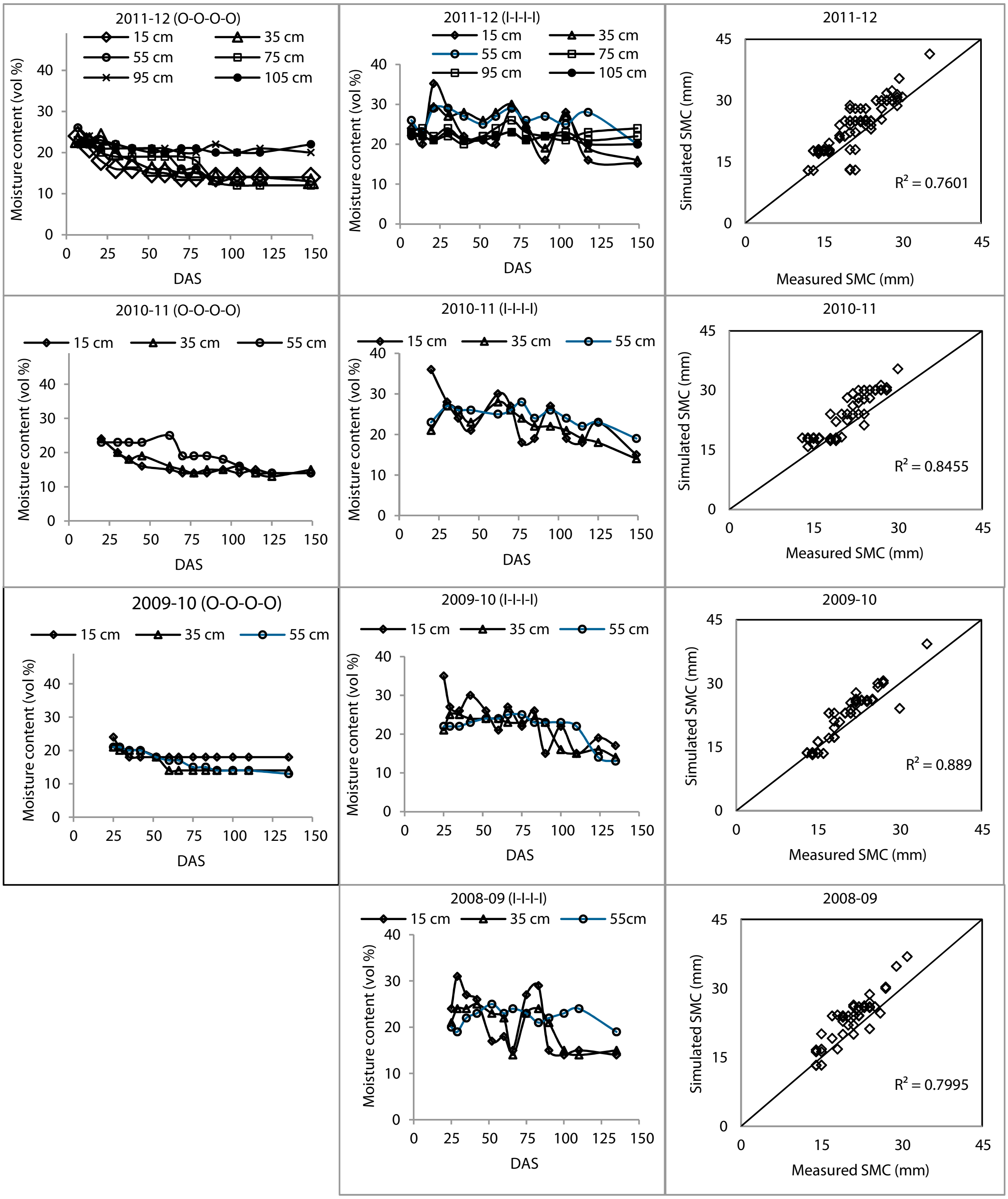


FIGURE 3. Fluctuations in soil water at different depths over the cropping season (expressed as days after sowing (DAS)) (left and centre), and the comparison between measured and simulated soil water content (SMC) (right)) along with statistical indicators for 2008–2012.

I–0.5I). Modelling efficiency was also lower at O–O–O–O (rain-fed) and I–0.5I–I–0.5I irrigation, and deviations between simulated and observed values were within 10 percent of measured values (Table 4). Since examining yield responses 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 (Geerts and Raes, 2009).

As observed in Figure 2, AquaCrop was able to simulate accurately the canopy cover (CC) development in the 2009–2010 and 2010–2011 cropping seasons. Simulated values of CC indicated slightly faster canopy development compared with the measured CC values. The overall relationship between measured and simulated values was very good with $R^2 > 0.90$ and a sufficient mean index of agreement (0.92). A similar trend was observed for in-season biomass and total biomass at harvest and grain yield (Table 4). The deviation between simulated and measured values was < 10 percent for

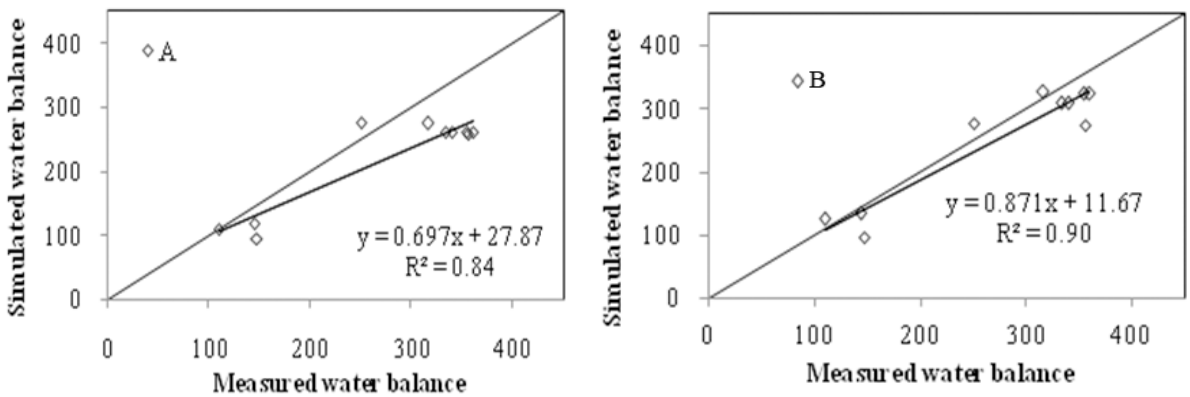


FIGURE 4. Total measured and simulated (AquaCrop) water balance (A: drainage excluded, B: drainage included) under different irrigation treatments during four-year study (2008–2012).

TABLE 4. Measured and AquaCrop simulated values of biomass and grain yield of wheat under different irrigation regimes during crop seasons 2008–2012

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	1.3	5.10	5.15	1.0
2009–10	Rain-fed	5.83	6.99	19.9	2.10	2.39	13.8
	I–I–I–I	11.98	12.86	7.4	4.68	4.89	4.5
2010–11	Rain-fed	6.07	7.38	19.1	1.89	2.10	4.9
	I–I–I–I	15.30	14.07	-2.5	5.70	5.51	5.0
2011–12	Rain-fed	6.53	7.27	11.9	1.97	2.25	12.5
	I–I–I–I	15.03	13.70	-8.7	5.46	5.42	-1.5
	I–0.5I–I–I	14.20	13.70	-3.5	5.23	5.42	4.2
	I–I–I–0.5I	14.36	13.70	-4.9	5.30	5.42	2.3
	1–0.5I–I–0.5I	14.10	13.69	-2.9	5.13	5.42	6.3

M = measured, S = simulated and D = percentage deviation between measured and simulated

both biomass and grain yield under irrigated treatment. In rain-fed conditions, higher deviations for biomass (19.9 percent) and grain yield (13.6 percent) were recorded in 2009–2010, but the deviation was reduced to 4.9 percent for grain yield in 2010–2011. The smaller deviations between measured and simulated biomass and grain yields (2010–2011) were due to better control of soil water balance and adjusting the rooting depth of the crop by *in-situ* measurements of wheat root growth under different irrigation treatments.

Evaporation and transpiration components

Crop growth models allow a combined assessment of different factors affecting yield (Liu *et al*., 2007), and also allow differentiating between evaporation and transpiration components of evapotranspiration. The patterns of evapotranspiration estimated using AquaCrop in the present study are presented in Figure 5. 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 as canopy cover increased. Transpiration remained higher during the vegetative growth and flowering stages and started declining at grain filling. The initiation of leaf senescence during the grain filling stage resulted in a decrease in transpiration with a corresponding increase in the evaporation component (Figure 5). An extensive sampling of soil, air and plant water at different crop growth stages was carried out to validate the AquaCrop evaporation and transpiration patterns with isotopic methods. The attempted Keeling plot gave variable estimates of evaporation and transpiration components; some data need reassessment and are not discussed here.

CONCLUSIONS

The present study showed that crop yield and water use efficiency of wheat could be improved by regulating plant-available water through irrigation at crop stages that are more sensitive (tillering and grain formation) to water deficit. The study demonstrated that up to 25 percent of the irrigation water can be saved by deficit irrigation when irrigation is applied at the less sensitive crop stage(s), thus allowing irrigating additional crop area. The proportion of water lost as soil evaporation (E) versus plant transpiration (T) relative to the total sum of evapotranspiration (ET) were quantified for the different irrigation treatments, such information can help to evaluate the effectiveness of land and water management practices that influence E and T components. The AquaCrop model can be a useful tool for assessing crop water requirements and devising regulated deficit irrigation strategies to enhance water productivity under different scenarios in water scarce areas.

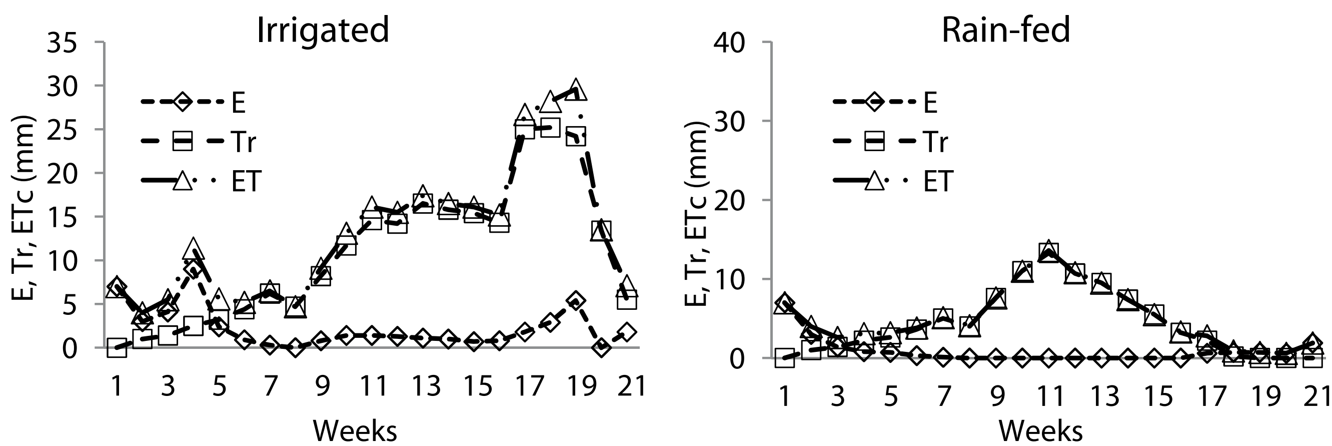


FIGURE 5. Pattern of wheat crop evapotranspiration and its components under rain-fed and irrigated conditions as determined by AquaCrop (2010–2011).

ACKNOWLEDGEMENTS

This research was partly funded by the International Atomic Energy Agency (IAEA), under the Coordinated Research Project (D1-20-09): Managing irrigation water to enhance crop productivity under water-limiting conditions: a role of isotopic techniques. The support from Dr. Minh-Long Nguyen (IAEA) and PAEC authorities is gratefully acknowledged.

REFERENCES

Farahani, H.J., Izzi, G. & Oweis, T.Y. 2009. Parameterization and evaluation of the AquaCrop Model for full and deficit irrigated cotton. *Agron. J.*, 101: 469–476.

Fereres, E. & Soriano, M.A. 2007. Deficit irrigation for reducing agricultural water use. *J. Exp. Bot.*, 58: 147–159.

Fereres, E., Orgaz, F. & Gonzalez-Dugo, V. 2011. Reflections on food security under water scarcity. *J. Exp. Bot.*, 62: 4079–4086.

Gallardo, M., Jackson, L.E., Schulbach, K., Snyder, R.L., Thompson, R.B. & Wyland, L.J. 1996. Production and water use in lettuces under variable water supply. *Irrig. Sci.*, 16: 125–137.

Geerts, S. & Raes, D. 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agr. Water Manage.*, 96: 1275–1284.

Geerts, S., Raes, D., Garcia, M., Miranda, R., Cusicanqui, J., Taboada, C., Mendoza, J., Huanca, R., Mamani, A., Octavio, C., Manani, J., Morales, B., Osco, V. & Steduto, P. 2009. Simulating yield response of quinoa (*Chenopodium quinoa* Willd.) to water availability with AquaCrop. *Agron. J.*, 101: 499–508.

Heng, L.K., Hsiao, T.C., Evett, S., Howell, T. & Steduto, P. 2009. Validating the FAO AquaCrop model for irrigated and water deficient field maize. *Agron. J.*, 101: 488–498.

Iqbal, M. & Munir, A. 2006. *Science & technology based agriculture vision of Pakistan and prospects of growth*. Islamabad, Pakistan Institute of Development Economics.

Lawless, C., Mikhail, A.S. & Pete, D.J. 2008. Quantifying the effect of uncertainty in soil moisture characteristics on plant growth using a crop simulation model. *Field Crops Res.,* 106: 138–147.

Liu, J., Wiberg, D., Zehnder, A. & Yang, H. 2007. Modeling the role of irrigation in winter wheat yield, crop water productivity, and production in China. *Irrig. Sci.*, 26: 21–33.

Steduto, P., Hsiao, T.C., Raes, D. & Fereres, E. 2009a. AquaCrop – the FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agron. J.*, 101: 426–437.

Steduto, P., Raes, D., Hsiao, T.C., Fereres, E., Heng, L., Izzi, G. & Hoogeveen, J. 2009b. AquaCrop: A new model for crop prediction under water deficit conditions. *Options Méditerranéennes*, Series A: 285–292.

Wallach, D. & Goffinet, B. 1989. Mean squared error of prediction as a criterion for evaluating and comparing system models. *Ecol. Model.*, 44: 200–306.

Willmott, C.J. 1981. On the validation of models. *Phys. Geogr.*, 2: 184–194.

Yield, Water and Nitrogen Use by Drip-irrigated Cabbage Grown under Different Levels of Applied Water

D.K. Asare[1,*], I.T. Larteh[1], J.O. Frimpong[1], M. Yaro[1], K.E. Banson[1], E.O. Ayeh[1] and L.K. Heng[2]

ABSTRACT

Drip irrigation, known for its efficient delivery of water to the root zone of crops, could be used for efficient management of scarce water that limits cabbage production and income levels for vegetable farmers during the dry season in Ghana. This study was conducted to evaluate the productivity, water use efficiency (WUE) and fertilizer nitrogen (N) use efficiency (FNUE) of cabbage cultivars KK-Cross and Oxylus, grown using small-scale drip irrigation system under variable water application levels in a coastal savannah environment of Ghana during the dry season. Total fresh yield (TFY), total dry matter (TDM), WUE and FNUE of cabbage cultivars decreased with decreasing levels of applied water. Linear models adequately described the relationship between TFY and seasonal crop evapotranspiration (ETc) as well as between TDM and ETc for these cultivars. The NFUE and WUE were linearly correlated with the KK-Cross cultivar; however, the models could not adequately describe the relationship between NFUE and WUE for Oxylus. The cabbage productivity under water limiting conditions could be enhanced through efficient use of applied N and water by adopting good water management strategies as ensured by the drip irrigation technology, there is also the need to formulate management strategies, including reducing farm size to match limited available water and to ensure efficient use of resources and high productivity by drip-irrigated cabbage.

Key words: *cabbage, water use efficiency, nitrogen use efficiency, drip irrigation, yield.*

INTRODUCTION

Cabbage production is a profitable venture during the dry season in the coastal savannah environment of Ghana but production levels are generally low (Vordzorgbe, 1997) due to factors that include inadequate availability of irrigation water and inefficient irrigation practices. Drip irrigation has the potential to increase water use efficiency (WUE) in vegetable production (Locascio, 2005) thereby reducing water use by 30–70 percent while increasing crop yields by more than 50 percent (Al-Rawahy, Abdel-Rahman and Al-Kalbani, 2004). Benefits from the application of low volumes of water to plant root zones include reduced soil surface evaporation losses and improved irrigation uniformity (Schwankl, Edstrom and Hopmans, 1996), and making drip irrigation suitable for the production of high value crops (Sanders, 1991), particularly under inadequate water supply. Knowledge of cabbage responses to different levels of applied water, and the associated use of applied nitrogen (N), could guide irrigation management strategies for optimizing cabbage yield and ensuring high efficiency of applied water and N use for the resource-poor farmers. This study was therefore undertaken to assess yield and water and N use efficiencies of two cabbage cultivars grown at different levels of applied water using a small-scale drip irrigation system.

MATERIALS AND METHODS

A field experiment was conducted at the Research Farm of the Biotechnology and Nuclear Agriculture Research Institute (BNARI), Ghana Atomic Energy Commission (GAEC). The experimental site is 76 m above sea level and situated on latitude 05°, 40’ N and longitude 0°, 13’ W in the coastal savannah environment of Ghana. Annual rainfall at the site ranges between 700 and 1 000 mm (Morris, Tripp and Dankyi, 1999). Additionally, the soil at the site is a well-drained sandy loam savannah Ochrosol (ferric acrisol) derived from quartzite schist (FAO/UNESCO, 1994), and known locally as the Haatso series.

A split-plot experimental design in three replicates was used, with the main plot being the levels of applied water (100, 85, 70, 55 and 40 percent of required water), and cabbage cultivars being the sub-plot. A small-scale drip irrigation system, occupying a total area of 525 m^2, was used to irrigate the cabbage cultivars at the various levels of applied water used for the study. A micro-plot, measuring 6 m x 0.8 m was established in each sub-plot for nitrogen-15 (^{15}N) fertilizer application and soil moisture monitored using a neutron probe (CPN Hydroprobe model 503DR).

Cabbage seedlings were transplanted at a spacing of 0.8 m x 0.6 m in each sub-plot on November 22, 2010 and harvested on February 19, 2011. Fertilizers applied were 120 kg/ha N, 100 kg/ha of potassium (K) and 50 kg/ha of phosphorus (P), one-third of which being applied two weeks after transplanting and the remaining two-thirds six weeks after transplanting of seedlings.

The potential crop evapotranspiration, ET_C, was estimated as:

$$ET_C = K_c \times ET_0 \quad (1)$$

where K_c is crop coefficient; ET_O is reference evapotranspiration (mm/day), computed using the previous day’s daily weather variables

1 Biotechnology and Nuclear Agriculture Research Institute, Ghana Atomic Energy Commission, Legon-Accra, Ghana
2 Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, IAEA, Vienna, Austria
* E-mail address of corresponding author: daniel_asare@yahoo.com

L.K. Heng, K. Sakadevan, G. Dercon and M.L. Nguyen (eds), Proceedings — International Symposium on Managing Soils for Food Security and Climate Change Adaptation and Mitigation. Food and Agriculture Organization of the United Nations, Rome, 2014: 297–301

based on the Penman-Monteith model (FAO, 1998), as given in Equation 2 (mm/day):

$$ET_0 = \frac{0.408\,\Delta(Rn - G) + \frac{890\gamma U\,(ea - ed)}{T + 273}}{\Delta + \gamma(1 + 0.339U)} \quad (2)$$

where Δ is slope of the saturated vapour pressure function (kPa/°C); γ is psychometric constant (kPa/°C); *Rn* is net solar radiation ($MJ \cdot m^{-2} \cdot d^{-1}$); *U* is wind speed (m/s) at 2.0 m height above the ground surface; *T* is mean daily temperature (°C); (*ea-ed*) is atmospheric vapour pressure deficit; and *G* is soil heat flux density ($MJ \cdot m^{-2} \cdot d^{-1}$), estimated according to Hargreaves and Merkley (2004) as:

$$G = 0.38(T_{day} - T3) \quad (3)$$

where T_{day} is mean air temperature on the day of calculation (°C); and *T3* is mean daily air temperatures of the previous three days (°C).

Soil moisture data was used to determine the actual crop water use (ET_a) (mm), based on the water balance approach:

$$ET_a = P + I \pm \Delta S \pm D \pm R \quad (4)$$

where *P* is precipitation (mm); *I* is irrigation (mm); *ΔS* is change in moisture stored in the soil profile (mm); *D* is deep drainage or capillary rise below the 100 cm soil profile (mm); and *R* is run-off (mm).

Run-off, deep drainage and capillary rise were assumed to be negligible and, therefore, set to zero since the experiment was conducted under dry conditions and water application was controlled using the small-scale drip irrigation system.

Sampling and analyses

Four cabbage plants (above ground and below ground) were harvested from each micro-plot and the samples oven-dried at 70°C for dry matter determination. Dry matter samples were also used for total N and ^{15}N analyses at the IAEA Laboratories in Seibersdorf, near Vienna, Austria. Additionally, cabbage plants were sampled at harvest from a 4.8 m^2 area in each sub-plot to determine total fresh yield.

Water and nitrogen use efficiencies

Water use efficiency (WUE) was estimated as follows on the basis of both total fresh yield (TFY) and total dry matter (TDM):

$$WUE_{TFY} = \frac{TFY}{ETc} \quad (5)$$

and

$$WUE_{TFY} = \frac{TDM}{ETc} \quad (6)$$

where WUE_{TFY} and WUE_{TDM} ($kg \cdot ha^{-1} \cdot mm^{-1}$) is WUEs based respectively, on *TFY* and *TDM*; and *ETc* is seasonal actual evapotranspiration (mm).

Fertilizer *N* use efficiency, *FNUE* (%), was estimated as:

$$FNUE = \frac{N_{YIELD} \times \%Ndff}{N_{APPLIED}} \quad (7)$$

and

$$\%Ndff = \frac{(\%N15AEPS) \times 100}{\%N15AEF} \quad (8)$$

where N_{YIELD} is total N uptake by plant (kg/ha); $N_{APPLIED}$ is amount of fertilizer applied (kg/ha); *%Ndff* is fraction of *N* in plant sample derived from the applied fertilizer; *%N15AEPS* is percent of ^{15}N atom excess in plant; and *%N15AEF* is percent ^{15}N atom excess in the fertilizer.

Statistical analyses

Total fresh yield (TFY), total dry matter (TDM), WUE_{TDM}, and FNUE were subjected to analysis of variance (ANOVA) based on the split-plot design and the least significant difference (LSD) used to separate means when significant differences were observed. The GENSTATS statistical package was employed in the analysis of the data. Also, linear regression and correlation analyses were used to assess the relationships between TFY and ETc, TDM and ETc and between NFUE and WUE.

RESULTS

Total fresh yield (TFY)

The five levels of water application (100, 85, 70, 55, and 40% of the optimal required level) were equivalent to 260.9, 222.5, 184.1, 145.7 and 107.3 mm, respectively of water applied. Water application levels were found to affect significantly the TFY of the cabbage cultivars, with the 100 percent water application level producing the highest TFY at 44.0 tons (t)/ha, followed by 33.0 t/ha for the 85 percent water application level (Table 1). Seventy percent and 55 percent water levels produced statistically similar TFYs of 20.4 t/ha and 19.3 t/ha, respectively. The 40 percent water application level produced the lowest TFY with 11.4 t/ha. For cabbage cultivars, the K-K Cross produced significantly higher TFYs (47.43 t/ha and 24.97 t/ha respectively at the 100 percent and 70 percent water application levels compared with corresponding values of 40.41 t/ha and 15.83 t/ha for Oxylus (Table 1). Furthermore, reducing the level of applied water by 15 percent from the 100 percent optimal level resulted in 33.5 percent and 15 percent decreases in TFY for KK-Cross and Oxylus, respectively. Similarly, TFYs produced by KK-Cross and Oxylus at 40 percent water application level were 24.5 percent and 27.6 percent, respectively of the TFY produced at the 100 percent water application level.

Total dry matter (TDM)

The 100 percent water application level produced the highest TDM of 4.23 t/ha ($p < 0.001$), followed by 3.27 t/ha, 2.05 t/ha, 2.07 t/ha and 1.37 t/ha produced by the 85, 70, 55 and 40 percent water application levels, respectively. The cabbage cultivars KK-Cross and Oxylus produced statistically different ($p < 0.05$) levels of TDM under both 100 percent and 85 percent water application levels (Table 1), with TDM for KK-Cross (4.59 t/ha) being higher than that for Oxylus at the 100 percent water application level (3.86 t/ha) while Oxylus produced a higher TDM (3.52 t/ha) than KK-Cross (3.02 t/ha) at the 85 percent water application level. In contrast, both cabbage cultivars produced statistically similar levels of TDM at each of the other water application levels (Table 1).

Water use efficiency based on total fresh yield (WUE_{TFY})

Water application levels significantly affected ($p < 0.001$) water use efficiency of the cabbage cultivars, WUE_{TFY} values at 100 percent and 85 percent being 131.80 $kg \cdot ha^{-1} \cdot mm^{-1}$ and 118.40 $kg \cdot ha^{-1} \cdot mm^{-1}$ and statistically similar (Table 1). Additionally, WUE_{TFY} at 70 percent and 55 percent water applications levels were respectively 86.40 $kg \cdot ha^{-1} \cdot mm^{-1}$ and 95.10 $kg \cdot ha^{-1} \cdot mm^{-1}$, but statistically similar, while the 40 percent water application level produced the lowest WUE_{TFY} value (63.20 $kg \cdot ha^{-1} \cdot mm^{-1}$). The KK-Cross cultivar had significantly higher WUE_{TFY} ($p < 0.009$) than Oxylus at the 100 percent water application level, but the cabbage cultivars had statistically similar WUE_{TFY} values at each of the other application levels (Table 1).

Water use efficiency based on total dry matter (WUE_{TDM})

Water use efficiencies based on TDM were statistically similar at all levels of water application. Comparatively, Oxylus had a significantly higher ($p < 0.05$) WUE_{TDM} value than KK-Cross only at the 85 percent level of applied water (14.37 and 11.65 $kg \cdot ha^{-1} \cdot mm^{-1}$, respectively) (Table 1).

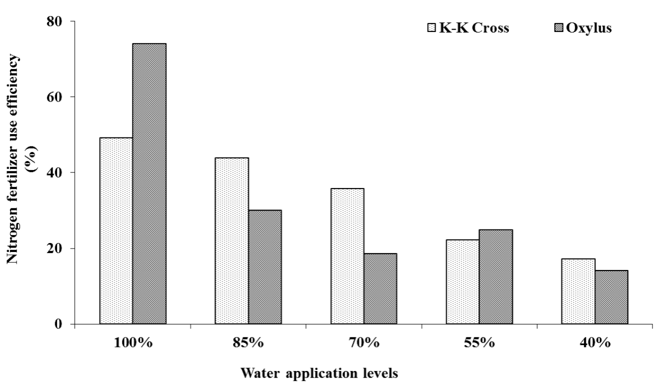


FIGURE 1. Nitrogen fertilizer use efficiency (NFUE) of cabbage cultivars KK-Cross and Oxylus at different levels of applied water.

Nitrogen fertilizer use efficiency (NFUE)

A significant difference ($p \leq 0.007$) was observed in NFUE values for the water application levels. At the 100 percent level of water application it produced the highest NFUE of 61.7 percent (Figure 1). Values for other water application levels were statistically similar and KK-Cross and Oxylus had statistically similar NFUE values at each water application level. Nitrogen use efficiency decreased from 60 percent at 100 percent water application level to as low as 18 percent at 40 percent water application level (Figure 1).

Linear regression and correlation analyses

Total fresh yield and TDM increased with increasing ETc whereas NFUE generally increased with increasing WUE_{TFY} and WUE_{TDM}. Linear models adequately described the functional relationship between TFY and ETc for the cabbage cultivars, as more than 60 percent of the data used for the analyses were accounted for by a linear model (Table 2). Similar results were obtained for the relationship between TDM and ETc for both cabbage cultivars (Table 2) as well as between NFUE and WUE_{TFY} and between NFUE and WUE_{TDM} for only the KK-Cross (Table 2). However, the relationship between NFUE and WUE_{TFY} and WUE_{TDM} for Oxylus could not be described adequately by a linear model, as shown by the poor R^2 value (Table 2).

DISCUSSION

Total fresh yield levels for the drip irrigated cabbage cultivars, which ranged between 11.15 t/ha and 47.43 t/ha across the 40–100 percent water application levels, were within the range of the mean world's cabbage yield level of 10–40 t/ha (de Lannoy, 2001) but lower than the 69 t/ha reported by Jangandi, Shekar and Shridhara (2000) and the 106 t/ha reported by Tiware, Singh and Mal (2003) for cultivars grown under plastic mulches with drip irrigation. The average values

TABLE 1. Total fresh yield (TFY), total dry matter (TDM), water use efficiencies based on total fresh yield (WUE_{TFY}) and total dry matter (WUE_{TDM}) for KK-Cross and Oxylus at varying levels of applied water. Adjacent values with same letters under a major heading are not significantly different.

Levels of applied water (%)	TFY (t/ha)		TDM (t/ha)		WUE_{TFY} ($kg \cdot ha^{-1} \cdot mm^{-1}$)		WUE_{TDM} ($kg \cdot ha^{-1} \cdot mm^{-1}$)	
	KK-Cross	Oxylus	KK-Cross	Oxylus	KK-Cross	Oxylus	KK-Cross	Oxylus
100	47.43a	40.41b	4.59a	3.86b	129.80a	106.90b	12.54a	10.22a
85	31.56a	34.34a	3.02a	3.52b	123.20a	140.4a	11.65a	14.37b
70	24.97a	15.83b	2.11a	1.99a	104.40a	68.50b	8.86a	8.60a
55	19.03a	19.58a	1.88a	2.25a	91.50a	98.70a	9.06a	11.33a
40	11.64a	11.15a	1.27a	1.47a	62.1a	64.30a	6.76a	8.48a

TABLE 2. Linear relationships between TFY and ETc, betweenTDM and ETc and between NFUE and WUE_{TFY} (WUE_{TDM})

No.	Relationship	Cabbage cultivar	Linear model	R^2
1	TFY vs. ETc	KK-Cross	$TFY = 0.155 \times ETc - 12.184$	0.657
		Oxylus	$TFY = 0.132 \times ETc - 8.288$	0.674
2	TDM vs. ETc	KK-Cross	$TDM = 0.016 \times ETc - 1.380$	0.747
		Oxylus	$TDM = 0.100 \times ETc + 0.079$	0.615
3	NFUE vs. WUE_{TFY}	KK-Cross	$NFUE = 0.488 \times WUE_{TFY} - 16.206$	0.930
		Oxylus	$NFUE = 0.334 \times WUE_{TFY} + 0.411$	0.186
4	NFUE vs. WUE_{TDM}	KK-Cross	$NFUE = 5.461 \times WUE_{TDM} - 19.698$	0.858
		Oxylus	$NFUE = 1.551 \times WUE_{TDM} + 15.961$	0.024

obtained were, however, close to the values of 30 t/ha obtained under drip irrigation with poultry manure (Ijoyah and Sophie, 2009), 32–37 t/ha under drip irrigation (Ijoyah and Rakotomavo, 2007) and 15–46 t/ha under sprinkler irrigation (Imtiyaz, 2000), and much higher than the 5.5 t/ha reported by Ogbodo, Okorie and Utobo (2009) for cabbage grown under rain-fed conditions. This suggests that drip irrigation has the potential to enhance the productivity of cabbage under limited water application levels.

Total dry matter is an indicator of a resource use by crops (Garnier *et al.,* 2001). Here, TDM levels of the cabbage cultivars ranged from 1.27 t/ha to 4.6 t/ha across the water application levels, higher than the 0.30–0.80 t/ha reported by Ogbodo, Okorie and Utobo (2009) for cabbage grown under rain-fed conditions, but generally within the range 1.5–10.5 t/ha reported by Franczuk *et al.* (2009) for cabbage grown under mulches.

Water use efficiency (WUE) is an important agricultural crop index (Hunsaker *et al.* 1996) which can be used to assess how soil water has been used for the production of total dry biomass and economic yield. The observed WUE_{TDM}, which ranged from 6.76 $kg·ha^{-1}·mm^{-1}$ to 14.37 $kg·ha^{-1}·mm^{-1}$, was generally lower than the range 12–50 $kg·ha^{-1}·mm^{-1}$ reported by Beletse, du Plooy and Mogatlane (2009), while values of WUE_{TFY} (range 64.30 to 140.40 $kg·ha^{-1}·mm^{-1}$) were higher than the 39–66 $kg·ha^{-1}·mm^{-1}$ reported by Imtiyaz *et al.* (2000). However, the values of WUE_{TFY} obtained in this study were far lower than the 427 $kg·ha^{-1}·mm^{-1}$ reported by Tiware, Singh and Mal (2003) for cabbage grown under drip irrigation using mulch; the difference could be due to a greater availability of soil water due to reduced soil surface evaporation from the use of surface mulch.

The NFUE value of 73.0 percent for Oxylus at the 100 percent water application level was higher than the value of 42.0 percent reported by Sturm *et al.* (2010) for cabbage grown under the practice of tank sprinkler irrigation. It was also higher than the values of 46.8 percent and 39.4 percent reported by Bing *et al.* (2005) for Chinese cabbage receiving 75 and 150 $kg·N·ha^{-1}$, respectively. However, the NFUE value of 48.0 percent for the K-K Cross cultivar at 100 percent water application level is in agreement with values reported by Bing *et al.* (2005) and Sturm *et al.* (2010). Furthermore, the range of NFUE values for K-K Cross (17.2–49.2 percent) and Oxylus (14.2–74.1 percent) across the levels of applied water considered in this study, are above the range of values of 18.1–24.6 percent reported by Bing *et al.* (2007) for Chinese cabbage grown in an open field.

The significantly higher NFUE for Oxylus compared with K-K Cross were due to the higher level of applied N taken by Oxylus. Similarly, the higher NFUE for K-K Cross at 85 and 70 percent water application levels compared with values for Oxylus resulted from higher uptake of applied N. The comparatively decreasing NFUE with decreasing levels of applied water observed here further emphasizes the need to ensure an adequate level of moisture in the soil through appropriate water management strategies in order to enhance the recovery of applied N fertilizer and ensure enhanced crop productivity.

CONCLUSIONS

Productivity, ETc, WUE and NFUE for cabbage cultivars K-K Cross and Oxylus were affected by levels of applied water. Reducing the level of water to 85 percent of optimal amount reduced the yield of these cultivars by around 33 percent and 15 percent, respectively. This suggests that a sharp decrease in the productivity of KK-Cross can arise from a slight reduction in the amount of water application. While the cabbage cultivars generally had similar WUEs at each level of water application, the K-K Cross specifically had significantly higher WUE_{TFY} values compared with Oxylus. NFUE generally increased with increasing WUE, emphasizing the importance of ensuring adequate soil moisture through appropriate water management strategies for enhanced crop productivity, WUE and NFUE. Additionally, the significant correlation between productivity and WUE emphasized the need to adopt improved water management practices that could simultaneously enhance productivity.

REFERENCES

Al-Rawahy, S.A., Abdel-Rahman, H.A. & Al-Kalbani, M.S. 2004. Cabbage (*Brassica oleracea* L. Capitata) response to soil moisture regime under surface and sub-surface point and line applications. *Int. J. Agric. & Biol.*, 6: 1093–1096.

Beletse, Y.G., Du Plooy, C.P. & Mogotlane, I.D. 2009. *Preliminary results on water use efficiency of four African leafy vegetables.* Proceedings Africa Crop Science Conference 9: 263–265.

Bing, C., Xue-Xia, J., Gui-Xin. C., Xiao-hui, F. & Hong-xia, S. 2005. Effects of low rate nitrogen application on *Brassica chinensis* growth and N losses. *Plant Nutr. Fert. Sci.,* 11: 519–523.

Bing, C., Fa-yun, H., Qiu-ming, X. & Q Ul-xin, C. 2007. Nitrogen use efficiency and N losses from Chinese cabbage grown in an open field. *Plant Nutr. Fert. Sci.*, 13: 1116–1122.

de Lannoy, G. 2001. Vegetables. *In*: Romain H. Raemaekers (ed.) *Crop production in tropical Africa,* pp. 467–75. Brussels, DGIC, Goekint Graphics NV Publisher.

FAO. 1998. Guidelines for computing crop water requirement requirements*,* by R.G Allen, L.S. Periere, D. Raes, & M. Smith, M. eds. *Irrigation and Drainage Paper No. 56*. Rome.

FAO/UNESCO. 1994. *Soil map of the world, revised legend.* World Resources Report 60, p. 146. Rome.

Franczuk, J., Jablonska-Ceglarek, R., Zaniewicz-Bajkowska, A., Kosterna, E. & Rosa, R. 2009. The effects of plant mulches on the nutritive value of red cabbage and onion. *Veg. Crops Res. Bull.,* 70: 125–134.

Garnier, E., Shipley, B., Roumet, C. & Laurent, G. 2001. A standardized protocol for the determination of specific leaf area and leaf dry matter content. *Funct. Ecol*., 15: 688–695.

Hargreaves, G.H. & Merkley, G.P. 2004. *Irrigation fundamentals: An applied technology for teaching irrigation at the international level,* p. 67. Logan, Utah, International Irrigation Centre, Department of Biological and Irrigation Engineering, Utah State University.

Hunsaker, D.J., Kimbell, B.A., Pinter Jr., P.J., La-Mante, R.L. & Wall, G.W. 1996. Carbon dioxide enrichment and irrigation effects on wheat evapotranspiration and water use efficiency. *Trans. Am. Soc. Agric. & Biol. Engin.,* 39: 1345–1355.

Ijoyah, M.O. & Rakotomavo, H. 2007. Yield performance of five cabbage (Brassica *oleracea* L. var capitata) varieties compared with local variety under open field conditions in Seychelles. *J. Sustain. Dev. Agric. & Environ.,* 3: 76–80.

Ijoyah, M.O. & Sophie, V.L. 2009. Effects of different levels of decomposed poultry manure on yield of cabbage (*Brassica oleracea* L. *var capitata*) at Anse Boileau, Seychelles. *J. Trop. Agric. Food Environ. Extens.,* 8: 20–23.

Imtiyaz, M., Mgadla, N.P., Manase, S.K., Chendo, K. & Mothobi, E.O. 2000. Yield and economic return of vegetable crops under variable irrigation. *Irrig. Sci*., 19: 87–93.

Jangandi, S., Shekar, B.C. & Shridhara, S. 2000. Water use efficiency and yield of cabbage as influenced by drip and furrow methods of irrigation. *Indian Agric*., 44: 153–155.

Locascio, J.S. 2005. Management of irrigation for vegetables: Past, present, future. *Hort. Technol.*, 15: 482–485.

Morris, M.L., Tripp, R. & Dankyi, A.A. 1999. *Adoption and impacts of improved maize production technology: A case study of Ghana Grains*

Development Project,. Economic Program Paper 99-01, pp 33–41. Mexico, CIMMYT/CRI/CIDA.

Ogbodo, E.N, Okorie, P.O. & Utobo, E.B. 2009. Evaluation of the adaptability of cabbage (*Brassica oleracea* L.*var capitata*) to the agro- ecology of Ebonyi State, South-eastern Nigeria. *Int. J. Sust. Agric*., 1: 41–48.

Sanders, D.C. 1992. Components and design considerations for drip irrigation. *Hort. Technol*., 2: 25–27.

Schwankl, L.J., Edstrom, J.P. & Hopmans, J.W. 1996. *Performance of micro-irrigation systems in almonds*. Proceedings 7th International Conference on Water and Irrigation, pp. 123–132. Tel Aviv, Israel.

Sturm, M., Kacjan- Marsic, N., Zupanc, V., Bracic- Zeleznik, B., Lojen, S. & Pintar, M. 2010. Effects of different fertilisation and irrigation practices on yield, nitrogen uptake and fertiliser use efficiency of white cabbage. *Scentia Horticulturae,* 125: 103–109.

Tiware, K. N., Singh, P. K. & Mal, P. K. 2003. Effects of drip irrigation on yield of cabbage (*Brassica oleracea* L.*var capitata)* under mulch and non- mulch conditions. *Agric. Water Manage.,* 58: 19–28.

Vordzorgbe, S.D. 1997. *Promoting intra- regional trade in agricultural products in West Africa: the case study of horticultural products in Ghana*. Paper presented at Workshop on Intra- regional Trade in Horticultural and Livestock Products. Ouagadougou, Burkina Faso and Accra, Ghana, 5–7August, 1997.

Water Use Efficiency of Coffee (*Robusta*) Under Mulch and Drip Irrigation on the Tay Nguyen Plateau, Viet Nam

D.N. Dang[1,*], H.S. Duong[2], M.C. Khuong[2], L.K. Heng[3], and M.L. Nguyen[3]

ABSTRACT

This paper attempts to separate the transpiration and evaporation components from total evapotranspiration (ET) and compares the water use efficiency (WUE) of coffee (*Robusta*) under furrow and drip irrigation practices, with and without mulching. The experiments were conducted on a 10-year old coffee plantation on a clay soil of the Tay Nguyen Plateau, in the central part of Viet Nam. The plantation is relatively homogeneous in terms of crop height, with a leaf area index (LAI) ranging from six to seven. The study showed that transpiration was the highest contribution (95 ± 5 percent) to ET during flowering (February–March), and the lowest (47 ± 3 percent) during the mature and canopy reformation stages (October–November), as separated by the isotopic technique. Drip irrigation (DrI) combined with plant residues (mulch) increased the WUE of coffee up to 2.13 kg clean bean per m^3 of irrigated water (kg/m^3), while WUEs under DrI and furrow irrigation (FI) without mulch were only 1.93 and 1.78 kg/m^3, respectively. Due to the improvement in WUE, the local farmers are making extra profit from the application of DrI with mulching from their coffee crop. Local farmers in the Tay Nguyen Plateau are now advised to use DrI with mulch from plant residues to all coffee plantations.

Key words: *coffee, water use efficiency, evapotranspiration, isotopic mass balance, drip irrigation, mulch.*

INTRODUCTION

Water is needed for plants to produce biomass and the role of water for getting high crop yields is recognized by farmers worldwide. In Viet Nam, wherever water is abundant farmers usually irrigate their crops excessively without thinking about the negative effects of over-irrigation such as runoff of fertilizer to the surface water causing eutrophication or leaching into deep aquifers leading to groundwater contamination. On the other hand, whenever water is scarce, for example during the dry season, farmers do not apply any measures to maintain or conserve soil moisture. The concept of water use efficiency (WUE) is still not familiar to Vietnamese farmers.

To improve WUE and produce the highest crop yield with the minimum amount of irrigated water, can be achieved through a number of approaches, e.g. deficit irrigation (DI) (FAO, 2002; Fereres and Soriano, 2007) and through covering the soil with plant residues or mulching (Edwards *et al.,* 2000; McIntyre *et al.*, 2000). All these practices are, in fact, aimed at minimizing evaporation (E) while maximizing the transpiration (T) components of total plant evapotranspiration (ET). To develop technological approaches for improving the WUE of a crop, it is therefore important to know the contributions of the E and/or T components to the ET of a crop, particularly in areas where water resources are scarce.

Currently, Viet Nam is the second biggest coffee exporter in the world. In 2011, 1.2 million metric tons (t) of coffee beans were exported, valued at $US2.7 billion on the London coffee market (VCA, 2011). Coffee is cultivated mainly on clay soil on the Tay Nguyen Plateau in the central part of Viet Nam, with a total area of 290 000 ha, at an elevation of 600–650 m above sea level (asl). Average air temperature is (23 ± 7)°C and rainfall is (2000 ± 120) mm but not evenly distributed over the year (NMB, 2011). Over the last few decades the climate in the country has become increasingly variable, e.g. extreme events such as heavier rain in the rainy season and typhoons from the Pacific Ocean hitting the country with unusual trajectories compared with those in the past, and have become more frequent (Ngu and Hieu, 2009). During the rainy season (April–August), rainfall over the Tay Nguyen Plateau is usually heavy, while during the dry season (September–March) there is almost no rain, requiring farmers to irrigate their coffee crop often during this period. The irrigation practice used by local farmers is furrow irrigation (FI). This has a low WUE, causing losses of soil and nutrients due to erosion and percolation of nutrients into the deeper soil profile and threatening groundwater quality deterioration.

The aim of the work reported here was to investigate cultivation practices that could improve the WUE of coffee plants, i.e. maximizing T while minimizing the E component of the crop. The investigations involved the following studies: (i) using an isotopic technique to separate E and T from the total ET of coffee plantation at different stages of their development cycle (mature, bean development, bean formation, flowering and bud development, and (ii) comparison of WUE of coffee plantations under drip irrigation (DrI) with mulch and that under the traditional furrow irrigation (FI) without mulch. The first study was to evaluate at what stage in the coffee development cycle the crop needed water most, i.e. when the T component was the highest. The second study aimed to establish whether DrI with scheduling in combination with mulch (abbreviated DrIS&M) had any advantage over the traditional FI and no mulch practice. It was hoped that the cooperation with the local farmers in conduct-

1 Vietnam Atomic Energy Institute, 59 Ly ThuongKiet, Ha Noi, Viet Nam
2 Institute for Water Resources and Environment, 117, Chua Boc, Ha Noi, Viet Nam
3 International Atomic Energy Agency, Wagramerstrasse 5, PO Box 100, 1400 Vienna, Austria
* E-mail address of the corresponding author: dangducnhan50@gmail.com

L.K. Heng, K. Sakadevan, G. Dercon and M.L. Nguyen (eds), Proceedings — International Symposium on Managing Soils for Food Security and Climate Change Adaptation and Mitigation. Food and Agriculture Organization of the United Nations, Rome, 2014: 303–307

ing this investigation would be the way to prove that application of advanced agronomic practices could improve the WUE of their coffee crop and increase their profit.

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

EXPERIMENTAL

Location

The experiment was conducted on a coffee plantation located in the town of Dak Ha in the Dak Ha district of Kon Tum Province (14°32’329N, 107°56’893E). The plantation is at an elevation of (630 ± 20) m asl, occupies an area of more than 100 ha and it belongs to several owners. The coffee variety is *Robusta*, planted on a clay soil in rows of 3 m × 3 m. The crop is 10 years old which is the most productive age. The trees were treated in such a way that their canopies just covered each other. The leaf area index (LAI) of the trees was between six and seven. Water used for irrigation was taken from a canal originating from a lake located around 2 km from the plantation. The canal passes under the foothill of the plantation.

Methods

The Keeling Plot method (Wang and Yakir, 2000; Williams *et al.*, 2004) was applied to separate E and T from the ET of the coffee trees. This method is 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 sources of evapotranspiration. The isotopic mass balance of each component is given as (Yakir and Sternberg, 2000):

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

where δ_{under}, δ_{above}, and δ_{ET} are the isotopic compositions of either deuterium (^2H) or oxygen-18 (^{18}O) in ‰ in the air moisture under, above the canopy, and in the atmospheric moisture or evapotranspiration, respectively, and C_{under} and C_{above} are the moisture content (mmole/m^3) under and above the canopy layers, respectively.

If the moisture content within the canopy (C_{under}) and its isotopic composition, e.g. of $\delta^{18}O$ (d_{under}) are known then one can construct a graph of δ_{under} *vs* 1/C_{under}, known as the "Keeling Plot". From this, the value of δ_{ET} can be derived as the intercept of the graph, and the contribution of the T component in percent (F_T, %)) to ET can be calculated as:

$$F_T, \% = \frac{\delta_{ET} - \delta_E}{\delta_T - \delta_E} x100 \quad (2)$$

where δ_E and δ_T denote the isotopic composition of soil evaporation and plant transpiration, respectively. The contribution of the E component to ET will be $F_E = (100 - F_T)$.

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

Atmospheric moisture along the canopy was collected using cryogenic traps and its isotopic composition (δ^2H and $\delta^{18}O$) was determined in the Laboratory of Isotope Hydrology, Institute for Nuclear Sciences and Technologies (INST) in Ha Noi. The air moisture content along the coffee canopy (C_{under}, mmole/m^3) was determined using a psychometric device that was designed and constructed by INST engineers. Details of the device are described below. In the experiment with mulch, the farmer was instructed to leave all branches and leaves after the canopy reforming stage on the land and not to clean up as is the normal practice. The thickness of the mulch was 5–8 cm.

Scheduling with DrI was based on the assumption that the plant needed to be watered when the refill point (RP) was down to half of the available soil water content (ASWC):

$$RP = 0.5\ ASWC \quad (3)$$

and ASWC was estimated as:

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

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

For a clay soil, the recommended ASWC ranges from 10-25 percent (FAO, 1985). The FC of clay soil in the coffee plantation was determined experimentally as 27 percent. The ASWC of the soil and rooting zone of the coffee plants was considered to be 12 percent and 2000 mm, respectively.

The amount of irrigation water in the DrIS was estimated for each watering time so that the trees were watered just enough to reach FC. With FI, it was left to the farmer to manage the timing and amount of water provided according to normal practice. Fertilizers used as well as the fertilization rate for the crop in the experiment were managed also by the farmer himself.

Soil moisture was measured and monitored using a neutron probe (PB-205, Fieldtech, Japan). To compare the WUE of the coffee crop under different management practices, (DrI&M and DrIS& no mulch *versus* FI), the experiment was conducted for three years (2009 to 2011). For each year, the total amount of irrigated water, [I (m^3/ha)] was recorded using water meters. The yield (Y) of the crop (kg/a) harvested during each harvesting season was recorded after processing to bean and air-drying. Irrigation WUE (Howell, 2001) was calculated as:

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

Instrumentation

Air temperature measurement and estimation of atmospheric moisture content

A "multi temperature device" was designed and assembled by engineers of the INST to estimate atmospheric moisture. As the height of the coffee trees was 2.2–2.5 m, the device was constructed with 12 chromel/alumel thermocouples installed at six positions along the canopy, i.e. at ground level 0 cm, 20 cm, 60 cm, 120 cm, 170 cm and 280 cm above the ground. The thermocouples were installed in pairs, i.e. at each sampling position one sensor measured "dry" while the other measured "wet" bulb temperatures. The wet bulbs were mounted on a piece of material immersed in a cup of water. This device functions like a traditional psychrometer used to determine air humidity in meteorological observations. The specific feature of the device is that it allows continuous recording of "dry" and "wet" temperatures as well as over variable time periods, e.g. 30 sec or 1 min etc. To do so, the thermocouples were connected to an electronic circuit that records the electrical signals appearing at the junction. Software was installed in a computer to convert the electrical signals into temperatures in Celsius degrees (°C). The device was calibrated in the Heat & Pressure Laboratory of the Vietnam National Metrological Institute and the accuracy of measurements was ±0.1°C over the range of 15–40°C.

Estimates of atmospheric moisture at each sampling position were based on the "dry" and "wet" temperatures using the Calculator for the Properties of Moist Air Program (http://www.natmus.dk/cons/tp/atmcalc/atmocalc.htp).

Collection of 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 air temperature (^{O}C), relative air humidity (%), solar radiation (W/m), dew point (^{O}C), wind direction, wind speed (m/min), rain rate (mm/h) and total daily rain (mm), atmospheric pressure (mb), potential evapotranspiration ET_0 (mm) etc.

Atmospheric moisture collection

Atmospheric moisture was collected at six positions along the coffee canopy using cryogenic traps. The cooling agent used was liquid nitrogen stored in a Dewar flask covered by a polyurethane foam cap through which six glass tubes with caps were inserted for trapping the moisture. Figure 1 depicts the scheme of one the cryogenic traps used.

The moisture from six sampling positions along the coffee canopy condensed in the bottom of the glass tubes (Figure 1) and was transferred into 1 ml vials that were then tightly capped to avoid evaporation during storage in the field. These samples were analysed for isotopic composition in the laboratory in Ha Noi.

Sampling and extraction of moisture from soil and skin of coffee trees

Surface soil and skin of coffee trees are needed to determine composition of oxygen-18 or deuterium in evaporative ($\delta^{18}O_E$ or δ^2H_E) and transpirative water ($\delta^{18}O_T$ or δ^2H_T) which will be used to estimate F_T and F_E (Equation 2). Soil was collected at a depth of 20 cm below the surface using a metallic spoon and stored in 10 g capacity vials which were capped tightly to avoid moisture evaporation and then transported to the laboratory for moisture extraction.

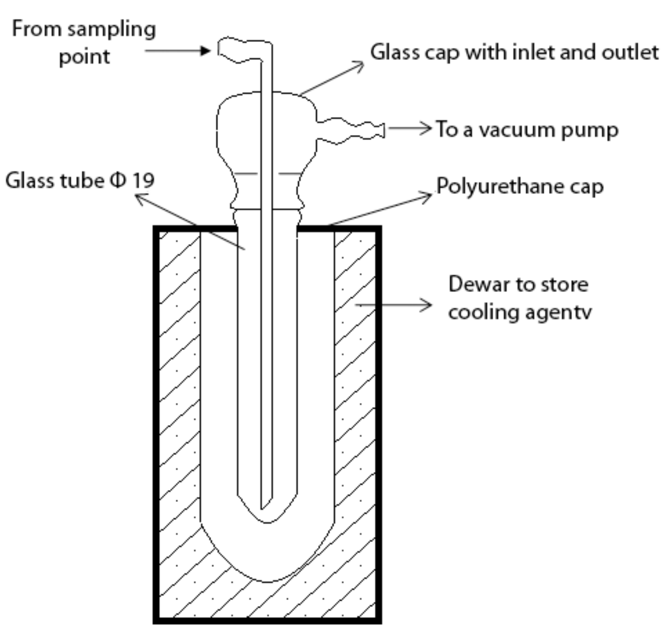


Figure 1. Diagram of a cryogenic trap used to collect atmospheric moisture along the coffee canopy.

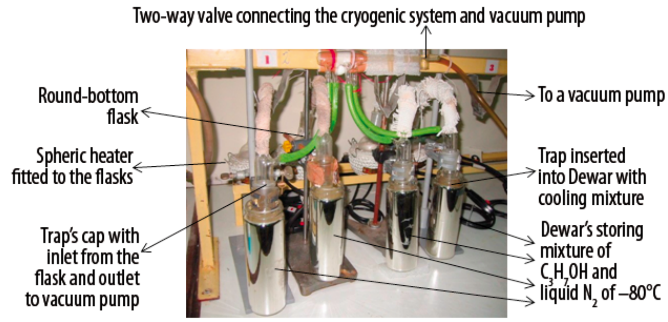


Figure 2. Cryo-distillation line used to extract moisture from soil and plant tissues before isotopic composition analysis.

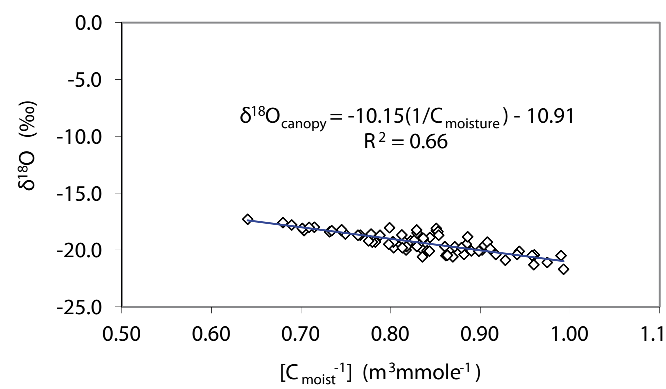


Figure 3. The Keeling Plot derived for 10-year old coffee plantation at the bean development stage with no irrigation.

Skin from secondary branches of the coffee plants was lightly scraped from dead tissue and then removed from the wooden part of the tree using a knife. The weight of the skin samples was around 3–4 g to obtain 0.5–1.0 ml of water after extraction.

Moisture was extracted using a cryogenic trapping technique and the device shown in Figure 2 which consists of a series of round bottom flasks connected to traps inserted in Dewar flasks cooled by a mixture of propane alcohol and liquid nitrogen at –80°C. This was connected to a vacuum pump to exhaust the air moisture inside before heating the flasks to 100°C. The vacuum was maintained at 25 milli bars (mb). The time needed to extract the moisture completely from soil and plant tissues was four hours and it was checked by parallel drying a part of the same samples overnight.

Analysis of isotopic composition of water samples

Water samples were analysed for their isotopic composition (δ^2H and $\delta^{18}O$) using an isotope ratio mass spectrometer supplied by GV Instruments (UK). The facility was equipped with an Elemental Analyzer (Eurovector, Italy) capable of pyrolysis of water into either hydrogen (1 050°C) on the nickel catalyst or carbon monoxide (CO) on glassy carbon (1 250°C), respectively. The precision of the analyses was ±2.0 and ±0.2‰ for δ^2H and $\delta^{18}O$, respectively. The accuracy of the analytical data was verified using Vienna Standard Mean Ocean Water (VSMOW) of the IAEA.

Table 1. Estimates of the $\delta^{18}O$ value of evapotranspiration (δ_{ET}) and the isotope values of plant transpiration (δ_T) and soil evaporation (δ_E) sources, and the corresponding T and E components (FT, FE, %) determined using Equation 2, before irrigation for the three important stages

Stage	$\delta^{18}O_{ET}$, ‰	$\delta^{18}O_{E+}$, ‰	$\delta^{18}O_T$, ‰	F_T, %	F_E, %
Mature and canopy reforming (September–November)	–11.64 (5)	–12.72 (10)	–10.43 (7)	47 (3)	53 (3)
Budding and flowering (December–February)	–9.71 (7)	–11.85 (6)	–10.52 (10)	85 (2)	15 (2)
Bean development (April–August)	–10.91 (3)	–13.85 (5)	–10.34 (5)	84 (2)	16 (2)

Figures in brackets are standard deviations in percent of mean values derived from three experiments during 2009–2011.

Table 2. Estimates of the $\delta^{18}O$ value of evapotranspiration (δ_{ET}) and the isotope values of plant transpiration (δ_T) and soil evaporation (δ_E) sources, and the corresponding T and E components (FT, FE, %) determined using Equation 2, before irrigation during the flowering stage, with and without mulch

Parameter	$\delta^{18}O_{ET}$, ‰	$\delta^{18}O_{E+}$, ‰	$\delta^{18}O_T$, ‰	F_T, %	F_E, %
With mulch	-9.42 (5)	-11.71 (7)	-9.27 (7)	94 (2)	6 (3)
Without mulch	-9.71 (7)	-11.85 (6)	-10.52 (10)	85 (2)	15 (2)

Figures in brackets are standard deviations in percent of the mean values derived from three experiments during 2009–2011.

RESULTS AND DISCUSSION

E and T components of coffee trees at different development stages

Figure 3 depicts the Keeling graph illustrating the relationship between composition of oxygen-18 ($\delta^{18}O$) in the air moisture along the coffee canopy and the reverse moisture content (m^3 $mMole^{-1}$).

The oxygen-18 composition in evapotranspirative moisture ($\delta^{18}O_{ET}$) was –10.91‰ (Figure 3), while the $\delta^{18}O$ of moisture in surface soil ($\delta^{18}O_E$) and from the skin of the plants ($\delta^{18}O_T$) were respectively –13.85 and –10.34‰. These data were used to estimate the contribution of individual T and E components (F_T and F_E) of the plant during the bean development stage (84 percent and 16 percent, respectively, Equation 2). This approach was applied for the coffee plantation at other stages and the results are summarized in Table 1.

During the mature and canopy reforming stages, T was lower (47 ± 3 percent) than E (53 ± 3 percent), while during the budding and flowering stages and bean development it was the reverse, i.e. T was higher than E (Table 1). Comparing E values during the three development stages, it is clear that in the budding and flowering stages following the bean development stage the crop needed more water than at other stages. However, the period of bean development coincides with the rainy season when the soil is saturated and the coffee can be sustained without irrigation. Hence, in order to have high yields of coffee bean, it is vital to irrigate the crop and maintain soil moisture at a level of at least 18–20 percent (Equation 4) during the flowering period.

Table 2 shows the T and E components of coffee trees in the flowering stage before irrigation (February–March) under mulch and no mulch as determined by the isotopic technique. As seen from Table 2 under mulch the T component was higher (94 ± 2 percent) than under the condition of no mulch (85 ± 2 percent), meaning that mulch improved the WUE of the coffee plants. Mulching with crop residues has been proven to be the cheapest way of reducing E since it lowers surface temperature, contributing the improvement of WUE (Hartkamp *et al.*, 2004). Reduction of E and increasing the T component by mulch can be explained by the fact that mulching materials generally reflect more solar radiation and have lower thermal conductivity than soil (Jalota and Prihar, 1998). Mulching with crop residues improves WUE of diverse crops, e.g. maize (Tolk, Howell and Evett, 1999; Deng *et al.*, 2006), wheat (Sun and Wang, 2001), rice (Xu *et al.*, 2007) and tomato (Baye, 2011).

Table 3 presents the variations in the T component of coffee plants during the flowering stage (February–March) under FI and DrIS practices. Uncertainty of the estimates was within 5–7 percent. Drip irrigation with scheduling combined with mulching (DrIS&M) increased the T component of coffee plants by around 10 percent compared with the FI and no mulch practice. However, the T in the DrIS, no mulch practice did not differ significantly, only 4 percent, from that of the traditional FI, no mulch practice (Table 3). This can be explained by the fact that the LAI of the crop was as high as 6–7 and the tree canopies covered each other making solar radiation on the soil surface to be almost the same in both cases. This is supported by the fact that soil surface temperatures in the FI and DrIS (no mulch) during the experiment were within almost the same range (26.8 ± 0.1)°C and (27 ± 0.2)°C, respectively. However, the soil sur-

Table 3. T and E components of coffee plants in the flowering stage under different irrigation practices

Irrigation practice	T (%)	E (%)
FI, no mulch	83	17
DrIS, no mulch	87	13
DrIS&M	94	6

Table 4. Coffee bean yield, amount of irrigated water and water use efficiency under different irrigation practices

Irrigation practices	Y (kg/ha)	Irrigation water, I (m^3/ha)	WUE (kg/m^3)
FI, no mulch	3550	1995	1.78
DrIS, no mulch	3630	1882	1.93
DrIS&M	3800	1784	2.13

face with FI was wetter than with DrI, suggesting that water was lost in the former mainly through runoff and/or infiltration.

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

The data used to estimate the WUE of coffee under different irrigation practices based on Equation 5 are shown in Table 4. The WUE of coffee plants under DrIS&M was the highest (2.13 kg/m^3), and the lowest under FI, no mulch (1.78 kg/m^3). Drip irrigation without mulch improved WUE by 8.4 percent, but DrIS&M improved by 19.7 percent compared with value under FI and no mulch. The lower yield of coffee bean under furrow irrigation and the lowest WUE of the crop might be due to furrow irrigation making soil within the rooting zone too wet and thereby preventing secondary root development. This would reduce water absorption and nutrient uptake by the plants. Moreover, under wet conditions root rot disease could occur as observed for Chile pepper with *Phytophthora* (Xie *et al.,* 1999) leading to lower crop yields.

As can be seen from Table 4 that if DrIS combined with mulching with plant residues were applied to the total 290 000 ha of coffee on the Tay Nguyen Plateau, 61 million m^3 of water could be saved and local farmers could increase their coffee bean yields by 72 500 tonnes, which, in turn, would be worth US$162 million on the London coffee market ($US2 250 per tonne).

CONCLUSIONS

Over a coffee cropping season the crop needs more water during the flowering stage and therefore supplementary irrigation is required to maintain soil moisture at a level of 18–20 percent, but not higher. Compared with the traditional furrow irrigation practice, drip irrigation combined with mulching plant residues reduced evaporation by almost 10 percent and improved irrigation WUE by up to 20 percent. This allowed local farmers to gain an extra profit amounting to around US$560/ha. Drip irrigation combined with plant residues mulch is advised for all coffee plantations on the Tay Nguyen area.

ACKNOWLEDGEMENT

This study was partly funded by the International Atomic Energy Agency. The authors would like to express their thanks to farmer, Mr. Dao Vinh Giang for allowing his coffee garden to be used for the experiment and for the care he took with fertilization and the operation of both furrow and drip irrigation technologies.

REFERENCES

Baye, B. 2011. Effect of mulching and amount of water on the yield of tomato under drip irrigation. *J. Hort. Forest.,* 37: 200–2006.

Deng, X-B., Shan, L., Zhang, H-P. & Turner, N.C. 2006. Improving agriculture water use efficiency in arid and semiarid areas of China. *Agric. Water Manage.,* 80: 23–40.

Edwards, L., Burney, J.R., Richter, G. & MacRae, A.H. 2000. Evaluation of compost and straw mulching on soil loss characteristics in erosion plots of potatoes in Prince Edwards Island, Canada. *Agric. Ecosystem. Environ.,* 81: 217–222.

Fereres, E. & Soriano, M.A. 2007. Deficit irrigation for reducing agricultural water use. *J. Exper. Bot.,* 58: 147–159.

FAO. 1985. *Irrigation water management: Introduction to irrigation*. FAO Corporate Document Repository (http://www.fao.org/DOCREP/R4082E/R4082 E00.htm)

FAO. 2002. *Scheduling deficit irrigation of fruit trees for optimizing water use efficiency*, by I. Goodwin & A.M. Boland. FAO Corporate Document Repository (http://www.fao.org/DOCREP/004/Y3655E/y3655e10.htm).

Hartkamp, A.D., White, J.W., Rossing, W.A.H., van Ittersum, M.K., Bakker, E.J. & Rabbinger, R. 2004. Regional application of a cropping systems simulation model: crop residues retention in maize production systems of Jalisco, Mexico. *Agric. Systems,* 82: 117–138.

Howell, T.A. 2001.Enhancing water use efficiency in irrigated agriculture. *Agron. J.*, 93:281–289.

Jalota, S.K. & Prihar, S.S. 1998.*Reducing soil water evaporation with tillage and straw mulching.* Ames, Iowa State University Press.142 pp.

McIntyre, B.D., Speijer, P.R., Riha, S.J. & Kizito, F. 2000. Effects of mulching on biomass, nutrients, and soil water in banana inoculated with nematodes. *Agron. J.,* 92:1081–1085.

National Meteorological Bureau (NMB) of Viet Nam*.* 2011. *Meteorological database of Viet Nam for the 2000–2010.*Ministry of Natural Resources and Environment, Ha Noi.

Ngu, N.D. & Hieu, N.T. 2009*. Climate change during the last 100 years in Viet Nam*. Ministry of Natural Resources and Environment, Ha Noi (in Vietnamese).

Sun, J. & Wang, Y.B. 2001. Effect of straw cover on wheat yield and soil environment in dryfield. *Trans. Chin. Soc. Agric. Eng.,* 17: 53–55.

Tolk, J.A., Howell, T.A. & Evett, S.R. 1999. Effect of mulch, irrigation, and soil type on water use and yield of maize. *Soil Till. Res.,* 50: 137–147.

Vietnam Coffee Association (VCA) 2011. *Coffee exports from Vietnam for 2011*. Annual Report to the Ministry of Trade and the Government. Ha Noi.

Wang, X.F. & Yakir, D. 2000. Using stable isotopes of water in evaporation studies. *Hydrol. Proc.,* 14: 1407–1421.

Williams, D.G., Cable, W., Hultine, H., Hoedjies, J.C.B., Yepez, E.A., Simonneaux, V., Er-Raki, S., Boulet, G., de Bruin, H.A.R., Chehbouni, A., Hartogensis, O.K. & Timouk, F. 2004. Evapotranspiration components determined by stable isotopes, sap flow and eddy covariance techniques. *Agric. Forest Meteorol.,* 125: 241–258.

Xie, J.H., Cardenas, E.S., Sammis, T.W., Wall, M.M., Lindsey, D.L. & Murrey, M.W. 1999. Effect of irrigation methods on chile pepper yield and *Phytophthora* root rot incidence. *Agric. Water Manage.,* 42: 127–142.

Xu, G.-W., Zhang, Z-C., Zhang, J-H. & Yang, J-C. 2007. Mulch improved water use efficiency of rice under non-flooded mulching cultivation. *J. Integ. Plant Biol.,* 49: 1527–1534.

Yakir, D. & Sternberg, L. de S.L. 2000. The use of stable isotopes to study ecosystem gas exchange. *Oecologia,* 123: 297–311.

Yield and Carbon Isotope Discrimination for Wheat, Barley and Lentil under Different Crop Sequences and Water Treatments in Northern Syria

A. Wahbi[1,*], M.A. Allo[2], A.N. Aldarir[2], A. Arslan[3] and A.S. Al Shaaban[4]

ABSTRACT

Improving water use efficiency is the main challenge in areas where water is the main production-limiting factor. This research was conducted on a research station in northern Syria between 2005 and 2009. The objective was to determine water use efficiency for different crop sequence rotations and the application of different levels of supplementary irrigation. The study used bread wheat (Sham 8 variety), a local lentil variety and barley (Arabic black variety). A randomized complete block design was used, involving six different cropping sequences with three replications and two levels of supplementary irrigation (75 percent and 55 percent of 90 percent of field capacity) and rain-fed as control. Soil water content was monitored using a neutron probe, and evapotranspiration was calculated. Grain samples (for the season 2007–2008 and for the two water treatments only) were used for measurement of grain carbon isotope discrimination (CID, Δ). Results showed that water treatments had significant (at 0.1 percent level) effects with yields increasing (in terms of grain and total biomass) with increasing water use efficiency (WUE) as more water became available. Carbon isotope discrimination, as an indirect measurement of transpiration efficiency, differed for different crops, with lentil having the highest range followed by barley and wheat. This suggests that lentil has a high elasticity in terms of transpiration efficiency compared with cereals. Positive relationships between Δ and yield were obtained, but more important were the slopes of the relationship between yield and CID (kg of yield per unit of CID) for the three crop species, with highest values being obtained for wheat and lowest for lentil. A simulation model for 19 yr of growing barley and wheat showed that there is a higher tendency for shortage of soil water, reaching permanent wilting point in the months of April and May for wheat compared with barley.

Key words: *wheat, lentil, barley, carbon isotope discrimination, supplementary irrigation, Syria.*

INTRODUCTION

Crop production in Mediterranean-type environments is invariably limited by low and erratic rainfall (200–500 mm/yr). Consequently, a major challenge is to devise cropping systems that maximize water use efficiency (WUE) (Deng *et al.,* 2005). Long-term weather data (over 30 yr) show that heavy rain showers (reaching 30–40 mm/d) followed by long periods of no rain cause soil erosion and water runoff, thereby increasing the risk of drought for crops in Syria (Wahbi, unpublished). Also, field experiments on a research station in northern Syria showed that soil evaporation varied as the season advanced and accounted for up to 70 percent of total evapotranspiration for barley despite optimum management (Wahbi, 1986).

Water productivity can be enhanced by manipulating the balance between the two components of water use, i.e. transpiration by crops and evaporation from the soil surface, through agronomic management and germplasm modification (Harris, 1994). For example, the use of different crop sequences could improve the use of nutrients and water resources. Legume crops play an important role in improving the sustainability of rain-fed dryland farming systems. Grain legumes conserve the soil, add organic matter, fix nitrogen (N), save soil N, and help in controlling cereal diseases (Diaz-Ambrona and Miniguez, 2001; Papastylianou, 1993). However, legumes are highly affected by water stress during the early and reproductive stages of growth (Leport *et al.,* 2003; Liu, Jensen and Andersen*,* 2003 and 2004), and replacing fallow by legumes in dryland farming systems can deplete soil water that could otherwise be available to the following cereal in the traditional wheat-fallow system. Therefore, any decision to introduce legumes or other annual crops into a rotation system either to reduce fallow or to break continuous cereal cropping must examine their potential effect on the efficiency of rain water use and system productivity. In addition, the many factors that influence WUE (Josh and Singh, 1994) must be considered. For instance, in a long-term trial in northern Syria, Pala *et al.* (2007) compared the effects of seven wheat-based rotations on soil water dynamics and WUE during both the wheat and non-wheat phases. On a system basis, the wheat-lentil or wheat-vetch systems were most efficient at using rainfall, producing 27 per cent more grain than the wheat-fallow system, while the wheat-chickpea system was as efficient as wheat-fallow system, and continuous wheat cropping was the least efficient. With N added to the cereal phase, the WUE of the

1 Department of Soil and Land Reclamation, Faculty of Agriculture, University of Aleppo, Syria
2 Department of Rural Engineering Faculty of Agriculture, University of Aleppo, Syria
3 Natural Resources, General Commission for Scientific Research (GCSAR), Ministry of Agriculture and Agrarian Reform, Syria
4 Department of Field Crops, Faculty of Agriculture, University of Aleppo, Syria
* E-mail address of corresponding author: wahbi@scs-net.org

system increased, but was still least for continuous wheat and greatest for wheat-lentil rotations. Wheat-legume rotation systems with additional N input during the wheat phase can therefore maintain sustainable production systems, but also are more efficient in utilizing the limited rainfall.

Many researchers (e.g. Condon, Richards and Farquhar, 1987; Farquhar, Ehleringer and Hubick, 1989) have suggested the use of carbon isotope discrimination (CID, $D^{13}C$ or Δ values) of leaf as an indirect measure of transpiration efficiency (TE, which is WUE at the leaf level) in water-limited environments. Ample information is available from CID analysis of plants about the relationship between TE, WUE and yield under different water regimes (e.g. Hall *et al*., 1994). However, results are inconsistent concerning the association between CID and yield for different crops and different growing conditions. (Hall *et al.,* 1994; Ngugi, Galwey and Austin, 1994 and 1996; Specht *et al*., 2001; Saranga *et al*., 2004; Monneveux *et al.,* 2007). They range from no relationship through to negative or positive relationships depending on the crop and the environment. Nevertheless, in Mediterranean environments positive relationships between the two were evident in many studies (Acevedo, 1991; Nachit, 1998; Merah *et al.,* 2001).

Genotypic variation in WUE under limited water regimes is affected more by variations in water use (WU) rather than by variations in biomass (Blum, 2005). This has also been determined for TE and stomatal conductance at the single leaf level (e.g. Juenger *et al*., 2005; Monclus *et al*., 2006; Monneveux *et al*., 2006). Hence, selection for high WUE under limited water supply tends to result in a genetic shift towards plant traits that limit crop WU (Ngugi, Galwey and Austin, 1994; Menendez and Hall, 1995). The successful and widely-cited case of dryland wheat grain yield improvement through selection for high WUE (low CID) in New South Wales, Australia (Condon *et al.*, 2002) can be explained by the fact that wheat grown there mainly relied on stored soil moisture.

A major avenue for yield improvement is the control of WU during the early growing season in order to avoid the lack of soil moisture during reproduction. This was attempted by selecting for reduced root xylem diameter (Richards and Passioura, 1989), but it can also be achieved by reducing leaf area and growth duration as carried out for sorghum grown under stored soil moisture conditions (Blum, 1970 and 1972; Blum and Naveh, 1976). Such plants optimize seasonal soil moisture use and achieved high WUE for grain yield due to their relatively moderate WU and high harvest index (HI). Yet, the same genetic materials selected for high WUE were not successful in Western Australia where the rainfed wheat was not grown on stored soil moisture (Condon *et al.,* 2002).

Considering all of the above, it is not surprising that drought resistance is associated with low WUE when analysed by CID under limited water supply (e.g. Ngugi *et al.*, 1994; Araus *et al.*, 2003; Solomon and Labuschagne, 2004). More recently, a drought-resistant Robusta coffee (C*offea canephora*) cultivar was found to have relatively lower WUE than a drought-susceptible cultivar, due presumably to greater WU associated with its deeper roots (Pinheiro *et al.,* 2005).

Finally, crop WUE has long been known to increase with increasing water stress (e.g. Meyers *et al.,* 1984), and this has been confirmed more recently by measurements of CID (Ismail, Hall and Bray, 1994; Craufurd *et al.*, 1999; Li *et al.,* 2000; Peuke, Gessler and Rennenberg, 2006). Assuming, therefore, that two different cultivars are planted side by side and exposed to drought, the cultivar with the higher WUE is likely to be relatively more stressed and at a lower plant water status than the drought susceptible one. In this regard, Blum (2009) argued that effective water use should be a major target for yield improvement in water-limited environments instead of WUE.

Supplementary irrigation is used in arid zones by applying small amounts of water during period of water stress to winter crops under rain-fed conditions (Oweis, Pala and Ryan, 1998). Deficit irrigation, i.e. irrigation with amounts less than required for full irrigation, may reduce water use by up to 50 percent of the amount used under full irrigation without reducing crop yield. Water productivity increases under deficit irrigation relative to full irrigation, as shown experimentally for many crops (Zwart and Bastiaanssen, 2004; Fereres and Soriano, 2007; Fan *et al.,* 2008). Also, water saving irrigation strategies such as regulated deficit irrigation can be used to irrigate only in drought-sensitive growing stages.

Supplementary irrigation of wheat in the Mediterranean region of Turkey increased grain yield by about 60 per cent depending on the level of rainfall and its distribution during the wheat growing season (November through May) (Sezen and Yazar, 1996). Concerning legumes, supplemental irrigation during the early and reproductive stages of their growth will reduce pod abortion and is expected to have a significant impact on final yield. The objective of this study was therefore to determine the effect of legumes on WUE in crop sequence rotations with wheat and barley by applying different levels of supplementary irrigation.

MATERIALS AND METHODS

Site

The research was conducted at the Makasem 5 Research Station in Hassakeh Province of northern Syria over four seasons started in 2005/2006. It is located in the Alkhabour basin, 8 km west of Hassakeh city, 36.5°N and 40.75°E. Long-term annual rainfall is around 272 mm during wet years and less than 150 mm in dry years. The irrigation water resource is ground water, with total salinity of about 3.5 dS/m.

Experimental design

Bread wheat (Sham 8), local lentil and barley (Arabic black) were used in the experiment. A randomized complete block design was used, with six different cropping sequences (wheat-wheat, wheat-lentil, barley-barley, barley-lentil, lentil-wheat, and lentil-barley) with three replications and two levels of supplementary irrigation (75 percent and 55 percent) of 90 percent of field capacity and rain-fed (as control treatment). There were 54 plots, the area of each irrigated plot being 164 m^2 (9 m x 18 m), whereas the rain-fed plot was 48 m^2 (6 m x 8 m).

Soil

Disturbed soil samples were taken before planting at increments of 15 cm to a depth of 105 cm. Samples were analysed to determine: pH and electrical conductivity (1:5); organic matter (%) using potassium di-chromate; Olsen-P; and available potassium (K) using wet digestion and atomic absorption spectrometry. Particle size analysis (hydrometer method) was used to determine silt, clay and sand percentages. Also the soil hydro-physical characteristics like field capacity, wilting point and total porosity were determined at the pre-planting stage.

Climate

Daily weather data minimum and maximum air temperatures, relative humidity, rainfall, and open pan evaporation were recorded throughout the experiment.

Agricultural practices

A local seeding machine was used with seeding rates of 200, 130, and 120 kg/ha for wheat, barley and lentil respectively and a row spacing of 20 cm. The amounts of fertilizer were calculated based on soil analysis before seeding.

Measurements

Soil moisture

Aluminium tubes were installed in each plot to a depth of 165 cm. A neutron probe (TROXLER-4300 type) was calibrated and used to monitor soil moisture at 15 cm increments throughout the season at about two-weekly intervals. Evapotranspiration (ET) was calculated using a standard soil water balance equation:

$$ET = AS + P + I - Dr$$

where *AS* is the change of soil water storage between the two neutron probe readings; *P* is precipitation (mm); *I* is the amount of irrigation (mm); and *Dr* is the drainage from the root zone. Since there was no drainage below the measured soil depth during the crop-growing seasons, Dr was set as zero. No surface runoff occurred throughout the seasons.

The neutron probe readings were used also to schedule irrigation of the 0–30 cm soil layer for the first crop period (from planting to tillering for wheat and barley, and to flowering for lentil), and of the 0–60 cm soil layer for the second crop period. Irrigation during the first crop period was scheduled when the volumetric soil water content reached about 23 percent and 17 percent for water treatments of 75 percent and 55 percent respectively, and about 22 percent and 16 percent for the second crop period.

Plant measurements

Grain and biological yields were determined by sampling at ground level, drying at 70°C and weighing. WUE was determined by dividing grain yield by evapotranspiration values.

Carbon isotope discrimination

Grain samples for the season 2007–2008 and for the two supplementary irrigation treatments only (since no grain yield was obtained for the rain-fed treatment) were dried and finely grounded for delta grain (ΔG) analysis at the International Atomic Energy Agency (IAEA) Laboratories, Seibersdorf.

Simulation model

Weather data from 19 years (1990–2009) were used to simulate crop production, water use (soil evaporation and plant transpiration), and the fraction of extractable soil water (FTSW) throughout the growing season. This last index is very important, since it indicates shortage of soil water when FTSW is below 0.1 and the frequency of this will indicate the need for either irrigation or a change of crop or management practice (Wahbi and Sinclair, 2007). The simulation model employed here had previously demonstrated close agreements between the measured and simulated biomass yields and evapotranspiration of barley and wheat crops with R^2 values greater than 80 percent (Wahbi and Sinclair, 2005).

Statistical analysis

Analysis of variance was done using GenStat V12 and the means compared by using least significant differences LSD at the level of five percent.

RESULTS AND DISCUSSION

Rainfall varied between seasons, being 104 mm in the 2006–2007 season and lower (less than 100 mm) during the 2007–2008 and 2008–2009 seasons; with an open class A pan evaporation reading reaching above 400 mm together with high temperatures, the crop failed on the rain-fed plot.

The soil was clayey at all depths (clay above 40 percent) except two layers (30–45 cm and 45–60 cm) which were loamy clayey (clay 34 percent, with high sand). Field capacity was 31.3–33.9 percent, electric conductivity was around 2.24 dS/m in most layers except for 0–15 cm which was 3.17 dS/m. Organic matter and Olsen-P were low, and K content was high to moderate.

Grain yield

In the rain-fed (control) treatment, yield was very low in the 2006–2007 season and in the next two seasons the crop failed. Overall, crop yield of 216, 1 342 and 2 603 kg/ha were obtained for the rain-fed, irrigation at 55 percent and at 75 percent, respectively. The influence of crop sequence was not clear, but there was a tendency for higher yields after lentil compared with continuous wheat or barley, and for lentil when barley was the preceding crop compared with wheat (data not shown).

Water use efficiency

Water use efficiency differed between seasons, but more important were the differences associated with irrigation treatments, crops, years and crop sequences, with WUE values being 1.4, 6.0 and 9.3 $kg{\cdot}ha^{-1}{\cdot}mm^{-1}$ for the rain-fed, 55 percent and 75 percent irrigation, respectively.

Crop failure occurred under rain-fed conditions during two seasons (2007–2008 and 2008–2009), and WUE was very low in 2006–2007 (no more than 1.8 $kg{\cdot}ha^{-1}{\cdot}mm^{-1}$). The WUEs associated with the 55 percent irrigation regime were 5.2, 6.2, and 8.0 $kg{\cdot}ha^{-1}{\cdot}mm^{-1}$ for the years 2006–2007, 2007–2008, and 2008–2009, respectively; with 75 percent irrigation, efficiencies were higher and progressively greater (7.6, 9.3 and 13.2 $kg{\cdot}ha^{-1}{\cdot}mm^{-1}$) between 2006–2007, 2007–2008, and 2008–2009, respectively (Table 1).

Carbon isotope discrimination (CID)

Carbon isotope discrimination values varied between 16.22‰ and 17.32‰ for barley in the irrigated blocks (55 percent treatment) and between 15.89‰ and18.02‰ under 75 percent treatment. For wheat the values varied between 16.76‰ and17.77‰ and between 17.84‰ and 18.18‰, respectively for the 55 percent and 75 percent treatments. For lentil, values were between 16.18‰ and16.87‰, and between 17.63‰ and19.28‰, respectively for the 55 percent and 75 percent treatments (Table 2). Carbon isotope discrimination values were slightly higher under the 75 percent treatments in all crops. Table 2 showed that lentil had the highest range which could mean more adaptable to irrigation conditions in this crop compared with wheat or barley.

Values for CID differed significantly between crops under 55 percent irrigation ($p < 0.01$) and also at 75 percent treatment ($p < 0.05$). Average CID values for the 55 percent treatment were 17.36‰, 16.62‰ and 16.45‰ for wheat, barley and lentil, respectively (Table 2). For the 75 percent treatment, CID values were 18.36‰, 17.98‰ and 17.29‰, respectively for wheat, lentil and barley.

TABLE 1. Water use efficiency for grain yield (kg·ha^{-1}·mm^{-1}) for three irrigation treatments and six crops sequences and three seasons (2006–2007; 2007–2008; and 2008–2009) at Makasim 5 research station

Season	Water Regimes	WUE for grain yield (kg·ha^{-1}·mm^{-1})		
		Barley	Lentil	Wheat
2006–2007	Rain-fed	1.54	3.23	0.72
	55%	5.09	7.56	2.97
	75%	8.16	10.58	3.94
2007–2008	Rain-fed	0	0	0
	55%	8.52	4.51	5.51
	75%	11.80	7.50	8.72
2008–2009	Rain-fed	0	0	0
	55%	7.96	11.13	4.84
	75%	13.75	15.54	10.25

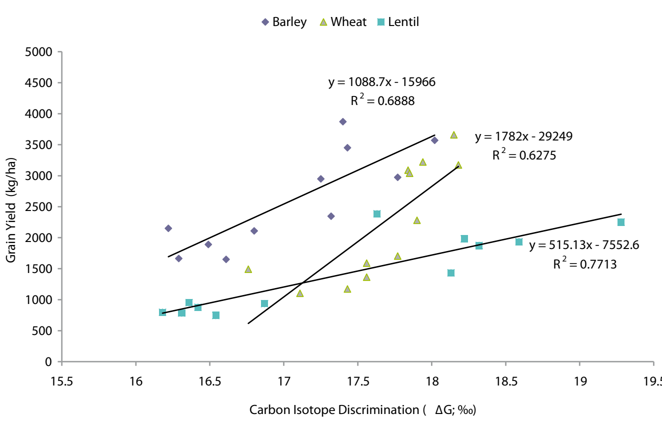


FIGURE 1. Relationships between grain yield (kg/ha) and ΔG (‰) for three crops in 2007–2008.

TABLE 2. Carbon isotope discrimination values (‰) for crops irrigated at 55 percent and 75 percent during 2007–2008

Crop	55 %	75 %
Barley	16.62	17.29
Wheat	17.37	18.36
Lentil	16.45	17.98
Fpr.	0.007 **	0.017 *
SED	0.239	0.303
LSD	0.532	0.676
CV (%)	2.5	2.9

Correlations and relationships

The relationship between grain yield and CID at 55 percent water treatment was positive but with a low R^2 value; a slightly better relationship was found at 75 percent water treatment (not shown). This indicates a higher efficiency for the increase in grain yield when CID increases at the higher water treatment (higher slope of the linear relationship) compared with the lower water treatment. However, the highest slope was found for wheat (1 782 kg/ha unit of CID), compared with 1088 kg/ha unit of CID and 515 kg/ha unit of CID for barley and lentil respectively (Figure 1).

Simulation model

Results of simulating the relationship between the fraction of transpired soil water (FTSW) and days after sowing of wheat and barley are shown in Figure 2. Wheat had the lower FTSW values indicating that barley was less exposed to drought than wheat in this area. Moreover, FTSW values for wheat were below 0.1 at about 108 d after sowing (early flowering), whereas for barley the time when FTSW values were below 0.1 was between 120 and 130 d after sowing (i.e. a period of only 10 d). Hence, application of supplementary irrigation at this time would be the most advantageous and would

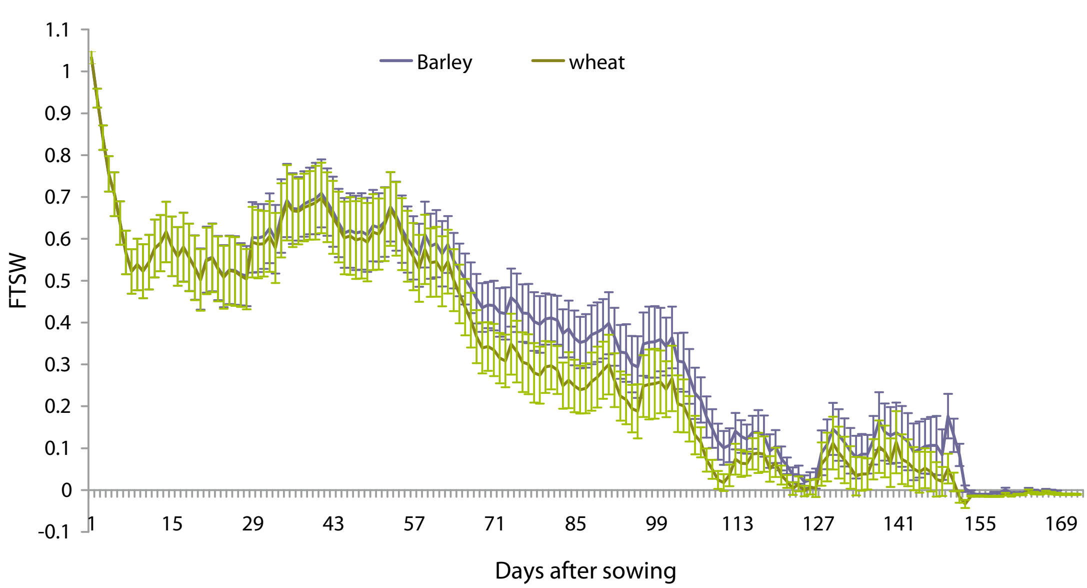


FIGURE 2. Relationships between average fraction of extractable soil water (FTSW) for barley and wheat and d after planting at Makasim 5 station. (simulation of 19 yr' data [1990-2009]; bars indicate standard error).

prevent crop death. Also, over the 19 yr of record-keeping, FTSW values fell below 0.1 on 42 and 28 d, respectively for wheat and barley. Most important, however, was the timing of the drought (below 0. 1 of FTSW, where water is not available for plants), and where barley was only severely affected from about 121–127 d after sowing whilst wheat was subjected to two severe periods of drought (at between 111 and 113 d and between 121 and 128 d after sowing) (Figure 2).

CONCLUSIONS

Irrigation had significant (at 0.1 percent level) effects on WUE and crop yields (in terms of grain and total biomass) which increased with increasing WUE. Values for CID differed between crops, with lentil having the highest range followed by barley and wheat. This suggests that lentil has a high elasticity in terms of transpiration efficiency compared with cereals. Positive relationships between Δ and yield were obtained, but more important were the slopes of the relationship between yield and CID (kg of yield per unit of CID) for the three crop species, with highest values being obtained for wheat and lowest for lentil. A simulation model can be used as a decision-support tool for crop selection under particular circumstances. Simulated results from 19 yr of growing barley and wheat showed that the tendency for soil water shortage to reach permanent wilting point during the months of April and May is higher for wheat compared with barley. This suggests using barley instead of wheat if no irrigation is available.

REFERENCES

Acevedo, E. 1991. Improvement of winter cereal crops in Mediterranean environments, use of yield, morphological and physiological traits. *In* E. Acevedo, A.P. Conesa, P. Monneveux & J.P. Srivastava, eds. *Physiology breeding of winter cereals for stressed Mediterranean environments*, pp. 273–305. Paris, INRA.

Araus, J.L., Villegas, D., Aparicio, N., Garcı´a Del Moral, L.F., El Hani, S., Rharrabti, Y., Ferrio, J.P. & Royo, C. 2003. Environmental factors determining carbon isotope discrimination and yield in durum wheat under Mediterranean conditions. *Crop Sci.*, 43: 170–180.

Blum, A. 1970. Effects of plant density and growth duration on sorghum yield under limited water supply. *Agron. J.*, 62: 333–336.

Blum, A. 1972. Effect of planting date on water-use and its efficiency in dryland grain sorghum. *Agron. J.*, 64: 775–778.

Blum, A. 2005. Drought resistance, water-use efficiency, and yield potential – are they compatible, dissonant, or mutually exclusive? *Aust. J. Agric. Res.*, 56: 1159–1168.

Blum, A. 2009. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. *Field Crops Res.*, 112: 119–123.

Blum, A. & Naveh, M. 1976. Improved water-use efficiency by promoted plant competition in dryland sorghum. *Agron. J.*, 68: 111–116.

Condon, A.G., Richards, R.A. & Farquhar, G.D. 1987. Carbon isotope discrimination is positively correlated with grain yield and dry matter production in field-grown wheat. *Crop Sci.*, 27: 996–1001.

Condon, A.G., Richards, R.A., Rebetzke, G.J. & Farquhar, G.D. 2002. Improving intrinsic water-use efficiency and crop yield. *Crop Sci.*, 42: 122–131.

Craufurd, P.Q., Wheeler, T.R., Ellis, R.H., Summerfield, R.J. & Williams, J.H. 1999. Effect of temperature and water deficit on water-use efficiency, carbon isotope discrimination and specific leaf area in peanut. *Crop Sci.*, 39: 136–142.

Deng, X-Ping, Shan, L., Zhang H. & Turner, N.C. 2005. Improving agricultural water use efficiency in arid and semiarid areas of China. *Agric. Water Manage.,* 80: 23–40.

Diaz-Ambrona, C.H. & Miniguez, M. 2001. Cereal–legume rotations in a Mediterranean environment: Biomass and yield production. *Field Crops Res.*, 70: 139–151.

Fan, X.W., Lia, F.M., Xionga, Y.C., Ana, L.Z. & Longa, R.J. 2008. The cooperative relation between non-hydraulic root signals and osmotic adjustment underwater stress improves grain formation for spring wheat varieties. *Physiol. Plant.*, 132: 283–292.

Farquhar, G.D., Ehleringer, J.R. & Hubick, K.T. 1989. Carbon isotope discrimination and photosynthesis. *Plant Mol. Biol.*, 40: 503–537.

Fereres, E. & Soriano, M.A. 2007. Deficit irrigation for reducing agricultural water use. *J. Exp. Bot.*, 58: 147–159.

Hall, A.E., Richards, R.A., Condon, A.G., Wright, G.C. & Farquhar, G.D. 1994. Carbon isotope discrimination and plant breeding. *Plant Breed. Rev.*, 12: 81–113.

Harris, H.C. 1994. Water use efficiency of rotations in a Mediterranean environment. *Aspects Appl. Biol.*, 38: 165–172.

Ismail, A.M., Hall, A.E. & Bray, E.A. 1994. Drought and pot size effects on transpiration efficiency and carbon isotope discrimination of cowpea accessions and hybrids. *Aust. J. Plant Physiol.*, 21: 23–35.

Josh, N.L. & Singh, D.V. 1994. Water use efficiency in relation to crop production in arid and semi-arid regions. *Ann. Arid Zone*, 33: 169–189.

Juenger, T.E., Mckay, J.K., Hausmann, N., Keurentjes, J.J.B., Sen, S., Stowe, K.A., Dawson, T.E., Simms, E.L. & Richards, J.H. 2005. Identification and characterization of QTL underlying whole-plant physiology in *Arabidopsis thaliana*, ^{13}C, stomatal conductance and transpiration efficiency. *Plant Cell Environ.*, 28: 697–708.

Leport, L., Turner, N.C., French, R.F., Thomson, B.D. & Siddique, K.H.M. 2003. Physiological responses of cool grain legumes to drought in the low rainfall Mediterranean environment of South Western Australia. *In Management of agricultural drought, agronomic and genetic options*, pp. 163–172. Delhi & Rome, ICRISAT & FAO.

Li, C.Y., Berninger, F., Koskela, J. & Sonninen, E. 2000. Drought responses of *Eucalyptus microtheca* provenances depend on seasonality of rainfall in their place of origin. *Aust. J. Plant Physiol.*, 27: 231–238.

Liu, F., Jensen, C.R. & Andersen, M.N. 2003. Hydraulic and chemical signals in the control of leaf expansion and stomatal conductance in soybean exposed to drought stress. *Funct. Plant Biol.*, 30: 65–73.

Liu, F., Jensen, C.R. & Andersen, M.N. 2004. Drought stress effect on carbohydrate concentrations in soybean leaves and pods during early reproductive development: Its implications in altering pod set. *Field Crops Res.*, 86: 1-13.

Menendez, C.M. & Hall, W.E. 1995. Heritability of carbon isotope discrimination and correlations with earliness in cowpea. *Crop Sci.*, 35: 673–678.

Merah, O., Deleens, E., Souyris, I., Nachit, M. & Monneveux, P. 2001. Stability of carbon isotope discrimination and grain yield in durum wheat. *Crop Sci.,* 41: 677–681.

Meyers, R.J.K., Foale, M.A. & Done, A.A. 1984. Response of grain sorghum to varying irrigation frequency in the Ord irrigation area. II. Evapotranspiration water-use efficiency. *Aust. J. Agric. Res.*, 35: 31–42.

Monclus, R., Dreyer, E., Villar, M., Delmotte, F.M., Delay, D., Petit, J.M., Barbaroux, C, Thiec, D., Brechet, C. & Brignolas, F. 2006. Impact of drought on productivity and water use efficiency in 29 genotypes of *Populus deltoides* x *Populus nigra*. *New Phytol.*, 169: 765–777.

Monneveux, P., Rekika, D., Acevedo, E. & Merah, O. 2006. Effect of drought on leaf gas exchange, carbon isotope discrimination, transpiration efficiency and productivity in field grown durum wheat genotypes. *Plant Sci.*, 170: 867–872.

Monneveux, P., Sheshshayee, M.S., Akhter, J. & Ribaut, J.M. 2007. Using carbon isotope discrimination to select maize (*Zea mays* L.) inbred lines and hybrids for drought tolerance. *Plant Sci.*, 173: 390–396.

Nachit, M.M. 1998. *Association of grain yield in dryland and carbon isotope discrimination with molecular markers in durum (Triticum turgidum L. var durum) wheat*. Proceedings 9th International Wheat Genetics Symposium, Saskatoon, Canada, pp. 218–223.

Ngugi, E.C.K., Austin, R.B., Galwey, N.W. & Hall, M.A. 1996. Associations between grain yield and carbon isotope discrimination in cowpea. *Eur. J. Agron.,* 5: 9–17.

Ngugi, E.C.K., Galwey, N.W. & Austin, R.B. 1994. Genotype x environment interaction in carbon isotope discrimination and seed yield in cowpea (*Vigna unguiculata* L. walp.). *Euphytica*, 73: 213–224.

Oweis, T., Pala, M. & Ryan, J. 1998. Stabilizing rainfed wheat yields with supplemental irrigation and nitrogen in a Mediterranean-type climate. *Agron. J.*, 90: 672–681.

Pala, M., Ryan, J., Zhang, H., Singh, M. & Harris, H.C. 2007. Water-use efficiency of wheat-based rotation systems in a Mediterranean environment. *Agric. Water Manage.,* 93: 136–144.

Papastylianou, I. 1993. Productivity requirements of barley in rainfed Mediterranean conditions. *Eur. J. Agron.*, 2: 119–129.

Peuke, A.D., Gessler, A. & Rennenberg, H. 2006. The effect of drought on C and N stable isotopes in different fractions of leaves, stems and roots of sensitive and tolerant beech ecotypes. *Plant Cell Environ.*, 29: 823–835.

Pinheiro, H.A., Damatta, F.M., Chaves, A.R.M. & Loureiro, M.E. 2005. Drought tolerance is associated with rooting depth and stomatal control of water use in clones of *Coffea canephora*. *Ann. Bot.*, 96: 101–108.

Richards, R.A. & Passioura, J.B. 1989. A breeding program to reduce the diameter of the major xylem vessel in the seminal roots of wheat and its effect on grain yield in rain-fed environments. *Aust. J. Agric. Res.*, 40: 943–950.

Saranga, Y., Jiang, C.X., Wright, R.J., Yakir, D. & Paterson, A.H. 2004. Genetic dissection of cotton physiological responses to arid conditions and their inter-relationships with productivity. *Plant Cell Environ.*, 27: 263–277.

Sezen, M. & Yazar, A. 1996. Wheat yield response to irrigation in the Mediterranean region of Turkey. *Turk. J. Agr. Forest.*, 20: 41–48.

Solomon, K.F. & Labuschagne, M.T. 2004. Variation in water use and transpiration efficiency among durum wheat genotypes grown under moisture stress and non-stress conditions. *J. Agric. Sci.*, 141: 31–41.

Specht, J.E., Chase, K., Macrander, M., Graef, G.L., Chung, J., Markwell, J.P., Germann, M., Orf, J.H. & Lark, K.G. 2001. Soybean response to water: A QTL analysis of drought tolerance. *Crop Sci.*, 41: 493–509.

Wahbi, A. 1986. *Varietal variation in root growth of barley and its influence on water use.* University of Reading, UK. (PhD thesis).

Wahbi, A. & Sinclair, T.R. 2005. Simulation analysis of relative yield advantage of barley and wheat in an eastern Mediterranean climate. *Field Crop. Res.,* 91: 287–296.

Wahbi, A. & Sinclair, T.R. 2007. Transpiration response of Arabidopsis, maize, and soybean to drying of artificial and mineral soil. *Environ. Exper. Bot.,* 59: 188–192.

Zwart, S.J. & Bastiaanssen, W.G.M. 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agr. Water Manage.*, 69: 115–133.

Evaluating Water Stress in Wheat Using Carbon Isotope Discrimination and other Crop Physiological Indices in the Central Anatolia Region of Turkey

S. Kale[1,*] , B. Sonmez[2], S. Madenoglu[2], K. Avag[2], G. Caycı[3], C. Kutuk[3] and U. Turker[4]

ABSTRACT

A study was carried out between 2009 and 2011 to evaluate the effect of different irrigation regimes on the carbon isotope discrimination ($\Delta^{13}C$) in leaf and grain samples, and the crop water stress index (CWSI), as indicators of water stress for wheat crop. The objective was to determine the relationship between CWSI and $\Delta^{13}C$ under field conditions and to calculate water-use efficiency (WUE [grain yield per unit evapotranspiration (ET)]) for wheat under different irrigation regimes (no irrigation, full irrigation, moderate and high water stress). The experiments were conducted at the Saraykoy Research Station in the Ankara-Murted Basin. Soil water content was measured with a neutron probe; while wheat canopy temperature and stomatal conductance were measured using infrared thermometer and porometer, respectively. The results suggest that water stress affects canopy temperature and stomatal resistance of the crop. Average canopy temperature was inversely correlated with stomatal conductance and can be used as indicators of stomatal closure in response to soil water deficit. The CWSI which is an index based on canopy surface temperature, is a promising tool for quantifying crop water stress. Carbon isotope discrimination values showed that grain and leaf $\Delta^{13}C$ can be used for selecting high wheat grain yield under water-limited conditions. Irrigating after-heading period is recommended to increase the WUE of wheat in the central Anatolia region of Turkey.

Key words: *carbon isotope ratio, wheat, stomatal conductance, water use efficiency (WUE), crop water stress index (CWSI).*

1 Department of Agricultural Structure and Irrigation, Agricultural Faculty of Suleyman Demirel University, East Campus, 32260, Isparta, Turkey
2 Soil, Fertilizer and Water Resources Research Institute of Ministry of Food and Agriculture, 5th km of Istanbul Road, 06172, Ankara, Turkey
3 Department of Soil Science, Agricultural Faculty of Ankara University, 06110, Ankara, Turkey
4 Department of Agricultural Machinery, Agricultural Faculty of Ankara University, 06110, Ankara, Turkey
* E-mail address of corresponding author: semakale@sdu.edu.tr

INTRODUCTION

In Turkey, particularly in the Central Anatolia region, lack of rainfall, drought and water scarcity are major climatic factors affecting crop production. The most important water management challenge for crop production in these arid and semi-arid regions is to use the limited water supply efficiently to maximize the yield per unit of water use. To achieve this, (i) it is necessary to know the effect of water use on the crop yield and to improve crop water productivity (to increase the marketable crop yield per unit water received by the crop), (ii) to reduce water losses from the crop root zone, and (iii) to increase soil water storage in the crop root zone by means of soil and water management practices.

For these reasons, cost effective and robust methods which can be used to reveal the effects of water stress on growth are needed during the crop growth period. The carbon isotopic technique has been shown to be useful for evaluating crop yield response to water stress and water use efficiency (Condon, Richards and Farquhar, 1987; Araus *et al.*, 1998). 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 drought-resistant crop species and breeding studies.

Similarly, canopy surface temperature measurements with infrared thermometers and other remote infrared sensors can be an important tool for detecting crop water stress. Crop water stress index (CWSI) is derived from canopy-air temperature differences versus the air vapor pressure deficit, was found to be a promising parameter for quantifying crop water stress (Jackson *et al.*, 1981; Idso and Reginato, 1982; Jackson, 1982). Gontia and Tiwari (2008) used the CWSI of wheat to schedule irrigation using infrared thermometry and Yuan *et al.* (2004) evaluated the application of three different forms of CWSI for monitoring water stress of winter wheat the North China Plain (NCP).

The response of crops to drought stress has also been assessed using stomatal conductance (Ashraf and Oleary, 1996; Kusvuran, 2012). During the early growth stage of wheat, stomatal conductance has been shown to be correlated positively with grain yield, grain numbers per spike, spike yield and spike length (Bahar, Yildirim and Baratcular, 2009).

The objective of this study is to evaluate the relationship between CWSI and $\Delta^{13}C$ for wheat grown under different water stress conditions and determine the respective WUE in the Central Anatolia Region of Turkey.

L.K. Heng, K. Sakadevan, G. Dercon and M.L. Nguyen (eds), Proceedings — International Symposium on Managing Soils for Food Security and Climate Change Adaptation and Mitigation. Food and Agriculture Organization of the United Nations, Rome, 2014: 315–321

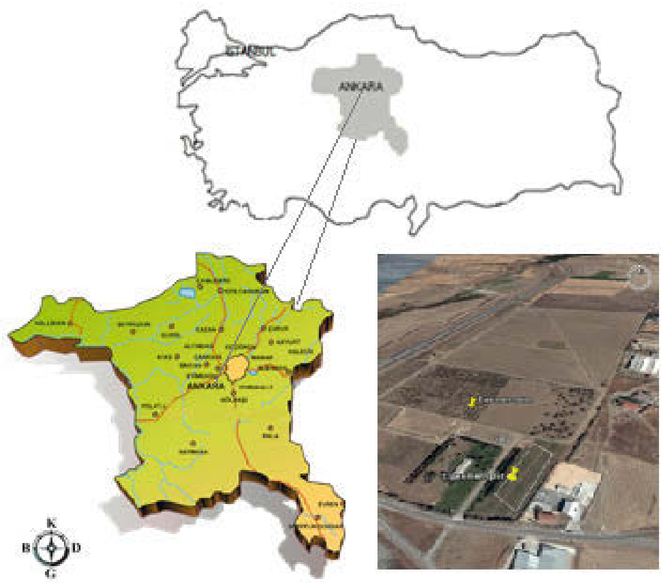


FIGURE 1. Experimental sites in the Ankara Murted Basin in the central Anatolia region of Turkey.

MATERIALS AND METHODS

Experimental site characteristics

Experimental sites were located in the Ankara Murted Basin (39° 57′ N and 32o 53′ E) of the Central Anatolia, Turkey (Figure 1). A field experiment was conducted to demonstrate the effect of water stress on yield and agronomic characteristics of wheat under different irrigation treatments during the period from October 2009 to July 2011 at the Research Farm Station of the Soil, Fertilizer and Water Resources Central Research Institute in Ankara, Turkey.

The soil of the experimental location ranges in texture from silty clay in the top 0.30 m followed by a layer of clay texture roughly 1.5 m deep. Field capacities (FC) and wilting points for different soil depths are provided in Table 1.

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

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

Surface irrigation was used in the study. The electrical conductivity of irrigated water was 1.76 dS/m.

Crop management and experimental design

The experiment consisted of four irrigation regimes with four replications, giving a total of 16 plots.

I_1 — No irrigation (Rain-fed)

I_2 — Full irrigation (water content was brought to field capacity after planting, and irrigated when calculated soil water depletion was 60 mm below FC)

I_3 — Limited irrigation (two irrigations maximum) one at tillering and another at grain filling

I_4 — No irrigation after establishment until heading, after which irrigation was applied when soil water depletion was 60 mm below FC.

Plot dimensions were 3.5 m × 5 m = 17.5 m^2 for seeding and 1.2 m × 4 m = 4.8 m^2 for harvesting. According to results of soil fertility analysis between 2008 and 2012 growing seasons, commercial N fertilizers were applied in bands about 10 cm to the side of the seed row (220 kg/ha ammonium sulphate were applied before sowing and a further 350 kg/ha were applied around middle of March of each year). Sufficient phosphates were applied (175 kg/ha DAP) to ensure adequate P nutrition.

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

Soil water content in the treatment 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 depths. The neutron probe measurements were made twice weekly at all the aforementioned depths. The neutron probe was calibrated annually before plot installation.

Crop water deficit was also monitored using a Fluke 66 model infrared thermometer. The crop canopy temperature measurements were taken at least 12 times from each treatment. Measurements were taken between 13.00 and 14.00 hours (h) on cloudless days. Canopy temperatures were used to determine crop water stress index (CWSI) which was computed using the method suggested by Idso *et al.* (1981):

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

where T_c is canopy temperature (°C); T_a is air temperature (°C); $(T_c–T_a)_{LL}$ is lower limit of canopy-air temperature difference; and $(T_c–Ta)_{UL}$ is upper limit of canopy-air temperature difference. The differences $(T_c–T_a)_{LL}$ were obtained from the linear regression for the crop under no water stress and $(T_c–T_a)_{UL}$ when the crop was under maximum water stress. The non-stressed baseline, $(T_c–T_a)$ versus vapour pressure deficit (lower limit) relationship was determined using data collected from the full irrigation (I_2) treatment. On the other hand, the fully stressed baseline (upper limit) was computed according to the method provided by Idso *et al.* (1981).

TABLE 1. Some physical properties of the soil

Depth (cm)	Texture	Bulk density (g/cm)	Field capacity (%)	Wilting point (%)
0–30	SiC	1.15	34.9	17.0
30–60	C	1.21	36.3	22.1
60–90	C	1.25	37.0	21.2

TABLE 2. The dates and amount of irrigation water applied for the various treatments

Irrigation water amounts (mm)									
2009–2010					2010–2011				
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	—	—
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

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

For isotopic measurements; 10–20 south-facing sun leaves of five marked plants per treatment were collected once at the stage of pre-anthesis (pre-emergence, second week of May). Only fully mature leaves from the latest growth period were used. Leaves were oven-dried at 60°C for 48 h and milled to a fine powder. Similarly grain samples after harvesting were collected for carbon isotopic analysis, carried out at the IAEA Seibersdorf Laboratory, Austria using isotope ratio mass spectrometer.

Carbon isotope ratios ($^{13}C/^{12}C$) of the samples ($^{13}C/^{12}C_{sample}$) and the standard ($^{13}C/^{12}C_{standard}$) values were converted into $\delta^{13}C$ (‰; per mil) using:

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

Delta carbon-13 ($\delta^{13}C$) values were transformed into the C isotope discrimination/difference (Δ) using the equation developed by Farquhar *et al.* (1982):

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

where subscripts a and p represent the isotopic ratios of air and plant, respectively. In the formula, –8‰ was used for air when transforming the $\delta^{13}C$ value into Δ (Keeling, Mock and Tans, 1979).

RESULTS AND DISCUSSION

Irrigation and rainfall

Amounts of water applied to various irrigation treatments and the timing of application are given in Table 2. The total rainfall occurred in the 2009–2010 growth period was 252 mm, and 289 mm for the same growth period in 2010–2011. Due to the higher than usual rainfall, the amount of irrigation applied was much less in 2010–2011 growing season.

The total soil water content over 90 cm depth declined to near wilting point values in the periods towards crop harvest in treatment I_1 (rain-fed) in 2009–2010 but the soil water content in the same treatment remained above wilting point even though no irrigation was applied in 2010–2011 (Figure 2). Soil water in the I_4 treatment did not reach the calculated soil water depletion of 60 mm until 19 June in 2011.

Crop water consumption

Monthly and seasonal crop water consumptions are given in Table 3. They were calculated according to the soil water budget, from changes in water content in the 0–90 cm soil depth. In both seasons, the highest water consumption occurred in the fully irrigated (I_2) treatment and the lowest in the rainfed treatment (I1).

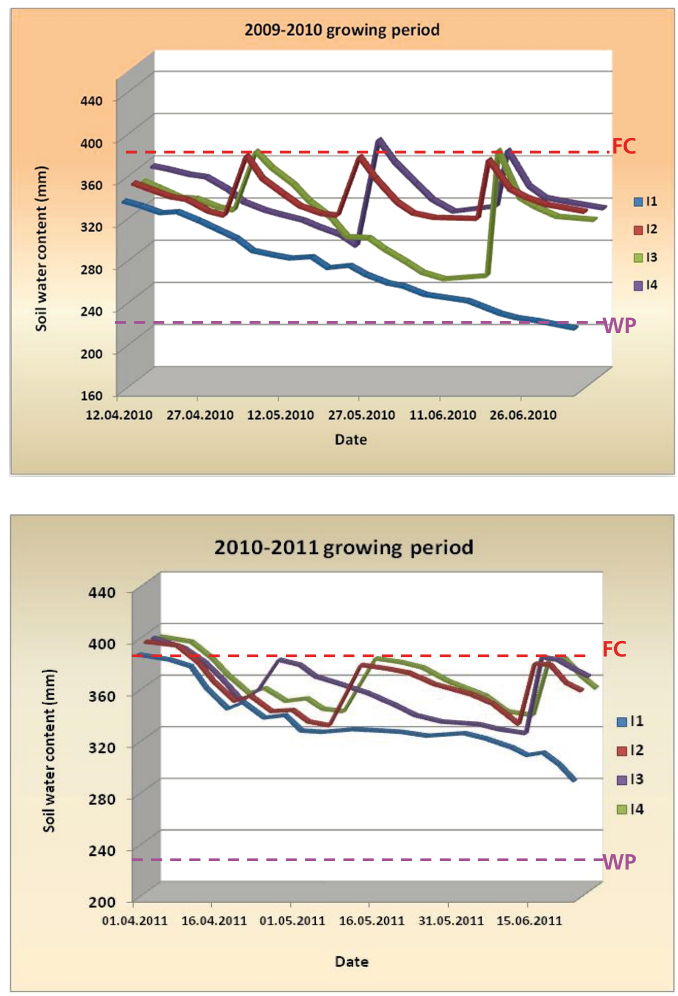


FIGURE 2. Total soil water storage to 90 cm depth during the growth periods 2009–2010 and 2010–2011.

Yield

The highest grain yield in both seasons (4.6 and 4.5 t/ha) was obtained from the fully irrigated (I_2) treatment (Table 4). Yield values for rain-fed (I_1) treatment were in general 23 percent, 15 percent and 19 percent, respectively lower than those from irrigated (I_2, I_3, I_4) treatments. However, there was no statistical significant differences ($p < 0.05$) in grain yield between I_2, I_3 and I_4 treatments I in both

TABLE 3. Monthly and seasonal wheat crop water consumption (ET) (mm) for the various treatments

Years	Treatments	ET (mm)							
		Oct.	Nov.	Dec.	Apr.	May	Jun	Jul**	Total
2009–2010	I1	33.39	61.78	112.44	60.61	58.01	70.27	25.84	422.3
	I2	49.47	77.96	112.43	125.67	120.14	95.29	27.89	608.8
	I3	37.48	49.88	110.55	122.64	119.75	112.35	21.98	574.6
	I4	33.31	57.82	106.37	68.60	92.25	107.23	20.71	486.3
2010–2011	I1	17.53	58.33	59.31	72.50	68.16	76.92	56.23	409.0
	I2	25.27	63.82	82.65	101.48	129.42	96.25	54.71	553.6
	I3	14.42	50.40	57.39	105.21	99.39	105.27	57.48	489.6
	I4	15.14	53.21	52.47	86.14	103.81	93.53	56.34	460.6

TABLE 4. Average yield, biomass and harvest index of the four irrigation treatments

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

TABLE 5. Water use efficiencies of four irrigation treatments

Years	Treatments	ET (mm)	Yields (t ha^{-1})	Irrigation (mm)	WUE (kg/m)
2009–2010	I_1	422	3.54	—	0.84^b
	I_2	609	4.58	290	0.75 ^{b}
	I_3	575	4.15	183	0.72 ^{b}
	I_4	486	4.36	162	0.90 ^{a}
2010–2011	I_1	409	3.16	—	0.77 ^{b}
	I_2	554	4.49	205	0.81 ^{b}
	I_3	490	4.28	120	0.87 ^{b}
	I_4	461	4.25	104	0.92 ^{a}

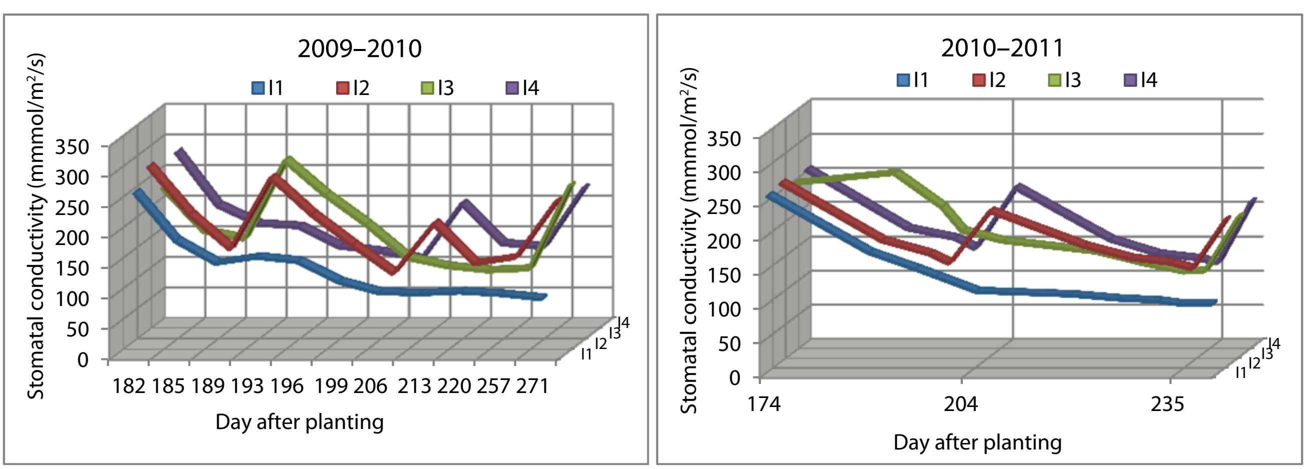


FIGURE 3. Change in stomatal conductance under different irrigation.

years. This was probably attributed to the high spring and winter precipitation in both years.

Harvest index (HI) values for the treatments were calculated using the average yield and biomass values in the respective treatments. They were 29, 31, 31 and 32 percent respectively for the four treatments. Although the highest HI was observed in treatment I_4, there was no statistical difference between all treatments (Table 4).

Water use efficiency (WUE)

Water use efficiency values calculated for both years are given in Table 5. The grain WUE ranged from 0.72 to 0.92 kg/m^3, with treatment I_4 (irrigation when the soil water deficit diminished to 60 mm during heading stage) having the highest WUE in both seasons. The results indicated the most effective water use by the winter wheat crop was obtained with treatment I_4. The above WUE is within the range obtained globally (0.40–1.83 kg/m^3) (Zwart and Bastiaans-

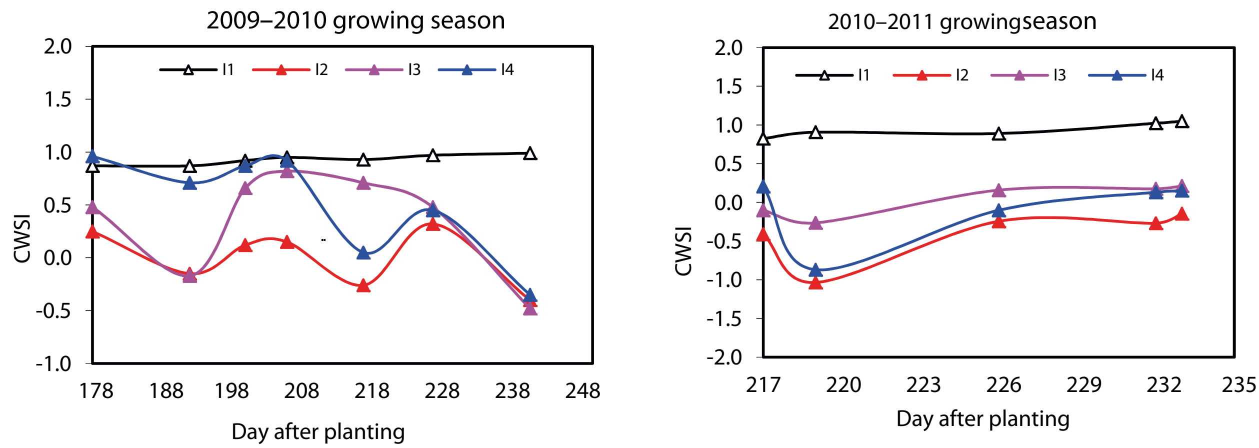


FIGURE 4. Variations in CWSI as a function of time after sowing for each irrigation treatment.

TABLE 6. Carbon isotope ratios of the leaf and grain samples

Years	Treatments	Δ ^{13}C–Leaf (‰)	Δ ^{13}C–Grain (‰)
2009–2010	I_1	19.81 ^{a}	17.94 ^{a}
	I_2	20.09 ^{a}	17.99 ^{a}
	I_3	19.85 ^{a}	18.47 ^{a}
	I_4	19.99 ^{a}	17.96 ^{a}
2010–2011	I_1	19.10 ^{b}	17.54 ^{a}
	I_2	19.97 ^{a}	18.04 ^{a}
	I_3	19.46 ^{ab}	17.76 ^{a}
	I_4	19.91 ^{a}	18.44 ^{a}

sen, 2004). In the Texas High Plains, rainfed winter wheat WUE was about 0.40 kg/m^3, while irrigated wheat WUE was 0.50–1.20 kg/m^3 with a yield of 3 000–8 000 kg/ha (Howell *et al.*, 1995).

Stomatal conductance

Figure 3 shows the changes in the stomatal conductance values taken twice per week on sunny and windless days in April (from the date irrigation was initiated), May and June (near senescence).

Stomatal conductance was the lowest for treatment without irrigation, suggesting that the pores became closed under least water available conditions. The highest stomatal conductance was obtained in fully irrigated treatment, especially after irrigation application.

Crop water stress index (CWSI)

The variations in CWSI as a function of time (day after planting) for each irrigation treatment are presented in Figure 4. In general, CWSI increases with increasing crop water stress as in rainfed treatment (I_1) and is lowest in fully irrigated treatment (I_2).

Evaluation of the carbon isotope ratios (Δ)

Carbon isotope ratio of leaves and grains of wheat are shown in Table 6. In general leaf Δ^{13}C is higher than grain Δ^{13}C for both years. Analysis of variance of Δ^{13}C for wheat leaves showed no statistical difference between the irrigation treatments in the first year; although there was a difference at the $p < 0.05$ level in the second year. Irrigation did not have a significant effect on the wheat Δ^{13}C leaf value, probably because the soil moisture did not fall low enough to cause discrimination. The analysis of variance also showed no statistical difference between the various irrigation treatments for both years with respect to grain Δ^{13}C values.

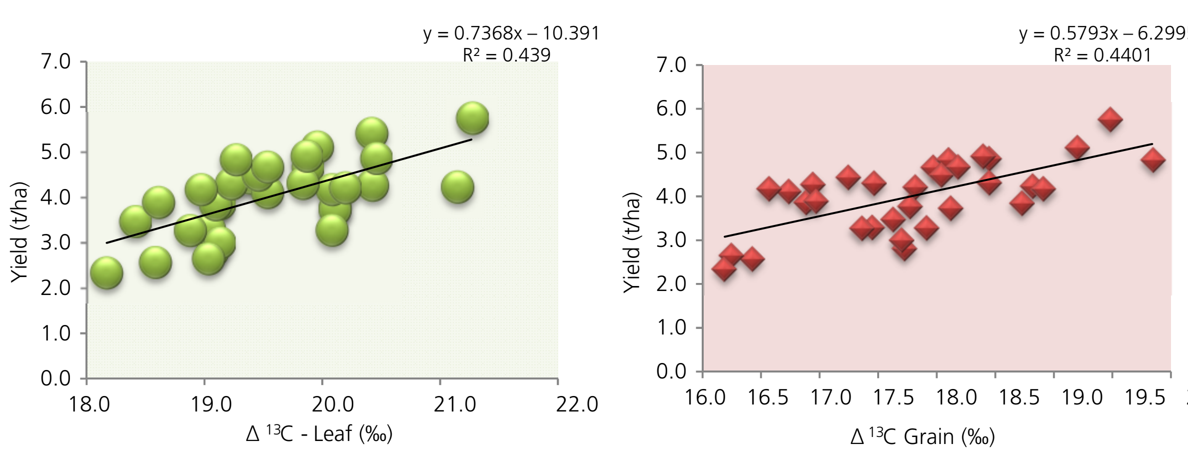


FIGURE 5. The relationships between Δ^{13}C values (in leaves and grain) and grain yield.

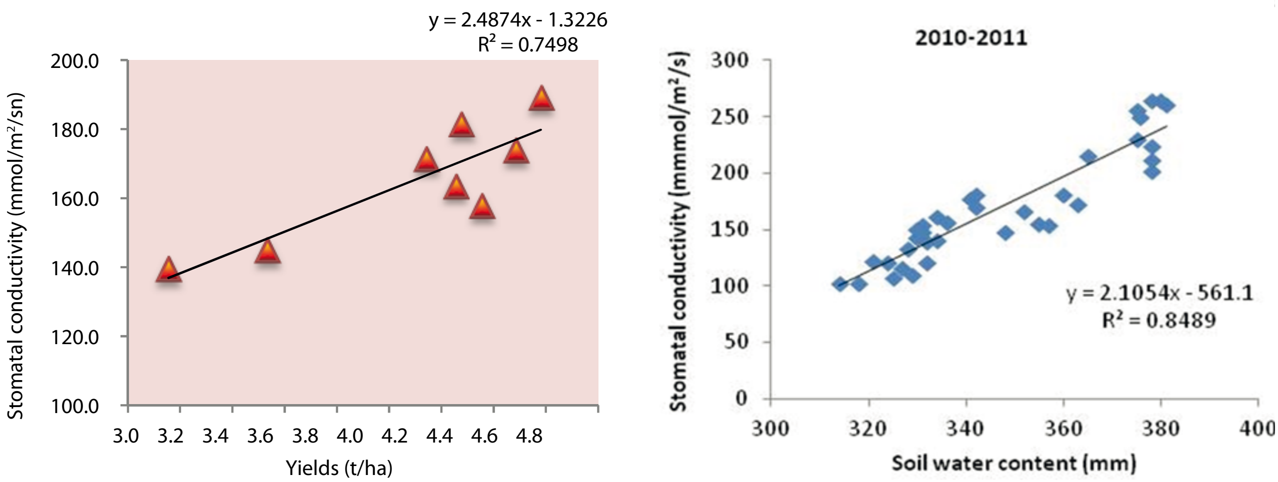


FIGURE 6. The relationship between stomatal conductance, yield (left) and soil water content (right).

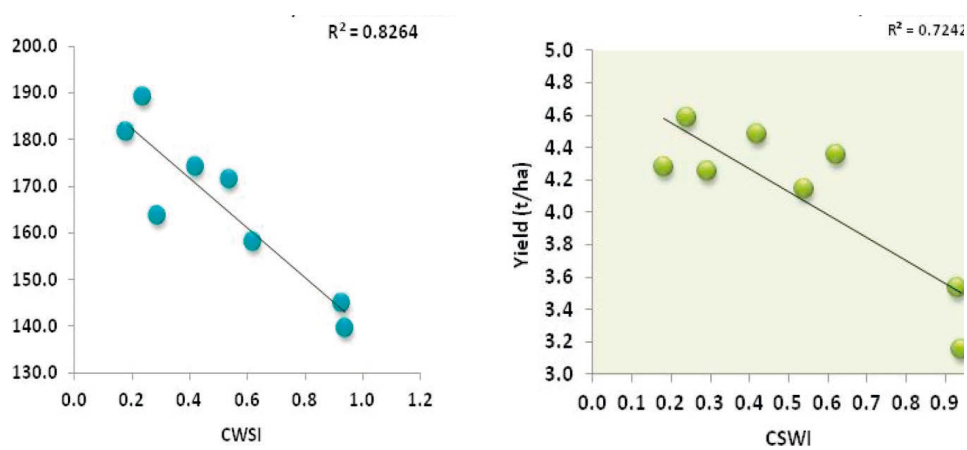


FIGURE 7. The relationship between CWSI and stomatal conductance (left) and grain yield (right).

The relationship between leaf and grain Δ values, yield and water use efficiency

There was a positive relationship between leaf and grain $\Delta^{13}C$ values and yields, as shown in Figure 5. A significant and positive relationship between leaf $\Delta^{13}C$ and grain yield was also observed for each individual treatment (data not shown). Positive relationships were often found between yield and $\Delta^{13}C$ under most climatic conditions (Sayre, Acevedo and Austin, 1995; Monneveux *et al*., 2005; Xu *et al*., 2007), especially under Mediterranean environments (Merah *et al*., 2001; IAEA, 2012).

A negative relationship was found between the WUE and $\Delta^{13}C$ values of both biomass and grain (data not shown). The relationship between the WUE and $\Delta^{13}C$ of wheat was also found to be negative by Ehdaie *et al*. (1991) and Khazaei *et al.* (2008).

The relationships between stomatal conductance, yield, CWSI, leaf Δ

A significant positive relationship was found between grain yield and stomatal conductance (Figure 6, left). The transpiration ratio increased with increased stomatal conductance which in turn was reflected in the yield. This positive relationship has also been reported (Shimshi and Ephrat, 1975; Evans, 1993; Lu *et al.,* 1998).

A positive relationship was also observed between soil water content and stomatal conductance (Figure 6, right) implying stomatal conductance is good indicator of overall moisture stress.

Similarly significant and negative relationship exists between CWSI and stomatal conductance and CWSI and grain yield for both years (Figure 7). This result agrees with many other studies (Howell, Musick and Tolk, 1986; Irmak, Dorota & Bastug, 2000), indicating that infrared thermometers can be used to quantify CWSI as a response of grain yield to water stress in wheat.

CONCLUSIONS

A study conducted during the wheat growth period for the years 2009–2010 and 2010–2011. In 2009-2010 seasons, full irrigation increased grain yield by more than 30%, however, insignificant yield difference between different irrigation inputs were observed in 2010–2011, attributed to high rainfall. The study showed a significant positive relationship between grain $\Delta^{13}C$ and grain yield, indicating that it is possible to select wheat varieties with the high yield potential using $\Delta^{13}C$.

The positive relationship between stomatal conductance and yield showed that water stress affects canopy temperature and stomatal resistance of the crop. Stomatal conductance is affected by temperatures of leaves which respond to soil water deficit. Average canopy temperature was inversely correlated with stomatal conductance.

The CWSI which is an index based on canopy surface temperature, is therefore a promising tool for quantifying crop water stress. Irrigation after-heading period may be used to increase WUE of wheat in the central Anatolia region of Turkey.

ACKNOWLEDGEMENTS

We gratefully acknowledge the technical and financial support of the International Atomic Energy Agency through Research Contract No. TUR/14463.

REFERENCES

Akhter, J., Sabir, S.A., Lateef, Z., Ashraf, M.Y. & Haq, M.H. 2008. Relationships between carbon isotope discrimination and grain yield, water-use efficiency and growth parameters in wheat (*Triticum Aestivum L.*) under different water regimes. *Pak. J. Bot.*, 40: 1441–1454.

Araus, J.L., Amaro, T., Casades'us, J., Absati, A. & Nachit, M.M. 1998. Relationship between ash content, carbon isotope discrimination and yield in durum wheat. *Aust. J. Plant Physiol.*, 25: 835–842.

Araus, J.L., Casades´us, J. & Bort, J. 2001. Recent tools for the screening of physiological traits determining yield. In: *Application of physiology in wheat breeding,* pp. 59–77. Mexico, CIMMYT.

Ashraf, M. & Oleary, J.W. 1996. Effect of drought stress on growth, water relations, and gas exchange of two lines of sunflower differing in degree of salt tolerance. *Int. J. Plant Sci.*, 157: 729–732.

Bahar, B., Yildirim, M. & Barutcular, C. 2009. Relationships between stomatal conductance and yield components in spring durum wheat under Mediterranean conditions. *Not. Bot. Hort. Agrobot. Cluj,* 37: 45–48.

Cabrera-Bosquet, L., Molerol, G., Bortl, J., Nogue, S.S. & Araus, J.L. 2007. The combined effect of constant water deficit and nitrogen supply on WUE, NUE and $\Delta^{13}C$ in durum wheat potted plants. *Ann. Appl. Biol.*, 151: 277–289.

Condon, A.G., Richards, R.A. & Farquhar, G.D. 1987. Carbon isotope discrimination is positively correlated with grain yield and dry matter production in field-grown wheat. *Crop Sci.,* 27: 996–1001.

Condon, A.G. & Richards, R.A. 1993. Exploiting genetic variation in transpiration efficiency in wheat: An agronomic view. *In:* J. Ehleringer, A. Hall & G. Farquhar, eds. *Stable isotopes and plant carbon-water relations,* pp. 435–456. San Diego, CA, Academic Press.

Condon, A.G., Richards, R.A., Rebetzke, G.J. & Farquhar, G.D. 2002. Improving intrinsic water-use efficiency and crop yield. *Crop Sci.*, 42: 122–131.

Ehdaie, B., Hall, A.E., Farquhar, G.D., Nguyen, H.T. & Waines, J.G. 1991. Water-use efficiency and carbon isotope discrimination in wheat. *Crop Sci.*, 31: 1282–1288.

Evans, L.T., ed. 1993. *Crop evolution, adaptation and yield*. England, Cambridge University Press. 514pp.

Gontia, N.K. & Tiwari, K.N. 2008. Development of crop water stress index of wheat crop for scheduling irrigation using infrared thermometry. *Agric. Water Manage.*, 95: 1144–1152.

Howell T.A., Musick, J.T. & Tolk, J.A. 1986. Canopy temperature of irrigated winter wheat. *Trans. ASAE*, 29: 1692–1698.

Howell, T.A., Steiner, J.L., Schneider, A.D. & Evett, S.R. 1995. Evapotranspiration of irrigated winter wheat: southern high plains. *Trans. ASAE* 38: 745–759.

IAEA, 2012. *Greater agronomic water use efficiency in wheat and rice using carbon isotope discrimination*. IAEA-TECDOC-1671, Vienna.

Idso, S.B. & Reginato, R.J. 1982. Soil and atmosphere-induced plant water stress in cotton as inferred from foliage temperatures. *Water Resour. Res.*, 18: 1143–1148.

Irmak, S., Dorota, Z.H. & Bastug, R. 2000. Determination of crop water stress index for irrigation timing and yield estimation of corn. *Agron. J.*, 92: 1221–1227.

Jackson, R.D. 1982. Canopy temperature and crop water stress. *Adv. Irrig.*, 1: 43–85.

Jackson, R.D., Idso, S.B., Reginato, R.J. & Pinter Jr., P.J. 1981. Canopy temperature as a crop water stress indicator. *Water Resour. Res.*, 17: 1133–1138.

Keeling, C.D., Mock, W.G. & Tans, P.P. 1979. Recent trends in the ^{13}C:^{12}C ratio of atmospheric carbon dioxide. *Nature*, 277: 121–123.

Khazaei H., Mohamma S.D., Zaharieva M. & Monneveux P. 2008. Carbon isotope discrimination and water use efficiency in Iranian diploid, tetraploid and hexaploid wheat grown under well-watered conditions. *Genet. Resour. Crop Evol.*, 56:105.

Kusvuran, S. 2012. Effects of drought and salt stresses on growth, stomatal conductance, leaf water and osmotic potentials of melon genotypes (*Cucumis melo* L.). *Afr. J. Agric. Res.,* 7: 775–781.

Lu, Z.M., Percy, R.G., Qualset, C.O. & Zeiger, E. 1998. Stomatal conductance predicts yields in irrigated pima cotton and bread wheat grown at high temperatures. *J. Exp. Bot.,* 49: 453–460.

Merah, O., Dele'ens, E., Souyris, I., Nachit, M. & Monneveux, P. 2001. Stability of carbon isotope discrimination and grain yield in durum wheat. *Crop Sci.,* 41: 677–681.

Monneveux, P., Reynolds, M.P., Trethowan, R., Gonzalez-Santoyo, H., Pena, R.J. & Zapata, F. 2005. Relationship between grain yield and carbon isotope discrimination in bread wheat under four water regimes. *Eur. J. Agron.*, 22: 231–242.

Sayre, K.D., Acevedo, E. & Austin, R.B. 1995. Carbon isotope discrimination and grain yield for three bread wheat germplasm groups grown at different levels of water stress. *Field Crops Res.*, 41: 45–54.

Shimshi, D. & Ephrat, J. 1975. Stomal behavior of wheat cultivars in relation to their transpiration, photosynthesis and yield. *Agron. J.*, 67: 326–331.

Xu, X., Yuan, H., Li, S., Trethowan, R. & Monneveux, P. 2007. Relationship between carbon isotope discrimination and grain yield in spring wheat cultivated under different water regimes. *J. Integr. Plant Biol.*, 49: 1497–1507.

Yuan, G., Luo, Y., Sun, X. & Tang, D. 2004. Evaluation of a crop water stress index for detecting water stress in winter wheat in the North China Plain. *Agric. Water Manage.*, 64: 29–40.

Yurtsever, N. 1984. *Statistical methods*. Ankara, General Directorate of Rural Services, Turkey 121: 89–110.

Zwart, S. J. & Bastiaanssen, G. M. 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agric. Water Manage.*, 69: 115–133.

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

L.K. Heng[1,*], T.C. Hsiao[2], D. Williams[3], E. Fereres[4], P. Cepuder[5], T. Denmead[6], N. Amenzou[7], N. Dhan[8], H. Duong[9], S. Kale[10], B.G. Li[11], K. Mahmood[12], X.R. Mei[13], E. Phiri[14], S. Zingore[15] and M.L. Nguyen[1]

ABSTRACT

This paper summarizes results obtained from an FAO/IAEA Coordinated Research Project (CRP) on "Managing Irrigation Water to Enhance Crop Productivity under Water-Limiting Conditions: A Role for Isotopic Techniques", implemented from 2007 to 2012. Its objective was to identify approaches to improve crop water productivity (production per unit of water input) under water-limiting conditions using isotopic and related techniques. The CRP employed both isotopic and conventional techniques to separate soil evaporation (E) and crop transpiration (T) and to help identify factors that minimize soil evaporation losses and improve irrigation management. Field measurement of E and T were carried out on a range of crops (maize, paprika, winter wheat and coffee) under different frequencies and methods of irrigation management practices and soil fertility levels. Using both nuclear, isotopic (Keeling plot and isotopic mass balance using delta oxygen-18 ($\delta^{18}O$)), the results showed that the proportion of evapotraspiration (ET) as E was much higher in the African studies (Malawi and Zambia) due to poor vegetation cover resulting from low soil fertility and inefficient irrigation management. However, by improving soil fertility, T increased by 50 percent in the Malawi maize study. In the North China Plain, through mulching, deficit irrigation and improved irrigation scheduling, soil E losses could be reduced by 10–30 percent of the total water loss compared with full irrigation. Soil E losses were also determined for 10-year old coffee trees in Central Vietnam over various growth stages. The E component was approximately 14 percent of ET during the bean development stage. When old branches and leaves were left as mulches on the ground, the T component could be as high as 92–95 percent compared with non-covered ground where total water loss through E could be three times more. The E and T results generated were also used to validate FAO's AquaCrop model for improving irrigation scheduling and agronomic practices. In the North China Plain, long-term simulation from AquaCrop showed that in wet years, only two irrigations at the planting and jointing stages were needed for wheat while no irrigation was needed for maize. In normal years, two irrigations were needed at the planting and jointing stages of wheat and one irrigation at the planting of maize, while in dry years, three irrigations were needed at the planting, jointing and booting stages for wheat and one irrigation at planting of maize.

Key words: *irrigation, evaporation and transpiration separation, $\delta^{18}O$ isotopic techniques, Keeling plot, isotopic mass balance.*

INTRODUCTION

Agriculture is the largest consumer of freshwater, accounting for about 75 percent of all withdrawals in developing countries. Water withdrawals are predicted to increase by 50 percent by 2025 in developing countries, and by 18 percent in developed countries (WWAP, 2006). There is an urgent need to improve agricultural water use efficiency (WUE) by increasing crop water productivity (CWP), i.e. the productivity of crop per unit of total water consumption (FAO, 2003). However, information on CWP and transpiration efficiency (TE), i.e. crop biomass per unit of transpired water under different irrigation technologies, and the extent and proportion of evapotranspiration

1 International Atomic Energy Agency, Wagramerstrasse 5, PO Box 100, 1400 Vienna, Austria
2 Department of Land, Air and Water Resources, University of California, Davis, USA
3 University of Wyoming Stable Isotope Facility, University of Wyoming, Laramie, USA
4 IAS-CSIC and University of Cordoba, Cordoba, Spain
5 Department of Water-Atmosphere-Environment, Institute for Hydraulics and Rural Water Management, Vienna, Austria
6 CSIRO Land and Water, Canberra, Australia
7 National Center of Study and Energy Nuclear, CNESTEN, Rabat, Morocco
8 Institute for Nuclear Science and Technology, HaNoi, Viet Nam
9 Center for Irrigation and Water Supply Research, HaNoi, Viet Nam
10 Department of Agricultural Structure and Irrigation, Agricultural Faculty of Suleyman Demirel University, Isparta, Turkey
11 Department of Soil and Water Science, College of Resources and Environment, China Agricultural University, Beijing, P. R. China
12 Nuclear Institute for Agriculture & Biology (NIAB), Faisalabad, Pakistan
13 Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Science (CAAS), Beijing, P. R. China
14 Department of Soil Science, University of Zambia, Lusaka, Zambia
15 International Plant Nutrition Institute (IPNI), Nairobi, Kenya
* E-mail address of corresponding author: L.Heng@iaea.org

L.K. Heng, K. Sakadevan, G. Dercon and M.L. Nguyen (eds), Proceedings — International Symposium on Managing Soils for Food Security and Climate Change Adaptation and Mitigation. Food and Agriculture Organization of the United Nations, Rome, 2014: 323–329

(ET) as soil evaporation (E) and transpiration (T) under different agro-climatic and soil–plant management conditions are often unavailable.

Loss of water from the soil surface through E is often a major component of the soil water balance in agricultural systems in semi-arid regions with sparse vegetation cover due to sub-optimal or inefficient management practices such as slow germination and slow growth rate due to poor soil fertility, wide row spacing due to low planting density and inappropriate irrigation and water conservation practices (Jackson and Wallace, 1999). The ability to distinguish between E and T can help to identify management practices that cut losses and improve WUE. However, accurate assessment of soil E is challenging due to sampling difficulties, spatial-temporal variability and the multiplicity of evaporation sources (Denmead *et al.*, 1996).

Stable isotopic tracer methods have been used to separate E and T (Moreira *et al.*, 1997; Williams *et al.*, 2004). 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 [δ^2H]). 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 (Wang and Yakir, 2000). With recent developments in laser absorption spectroscopy, real-time, *in situ* and continuous measurements of $\delta^{18}O$ and δ^2H in air vapour and liquid water are now possible, allowing continuous ET partitioning on a diurnal basis. Two isotopic methods: the Keeling plots (Keeling, 1961; Williams *et al.*, 2004) and isotopic mass balance (IMB; Hsieh *et al.*, 1998; Ferretti *et al.,* 2003) were used in this CRP. Results of the separation of E and T using these isotopic methods as well as those using conventional methods (e.g. using soil moisture sensors, eddy covariance and micro-lysimeters) are reported in this paper.

The FAO's AquaCrop model (Raes *et al.,* 2009; Steduto *et al.*, 2009) on crop yield response to water was used to improve irrigation scheduling and agronomic practices in several studies.

MATERIALS AND METHODS

The research network in the CRP included seven research contract holders (two from China and one each from Malawi, Morocco, Pakistan, Turkey, Vietnam and Zambia), supported by one technical contract holder (Australia) and four research agreement holders (Austria, Spain and two from the United States). The objectives of the CRP were to (i) quantify and develop means to manage soil evaporative (E) losses to maximize the beneficial use of the transpirational (T) 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).

Keeling plot method

The Keeling plot method is based on the isotopic mass balance mixing relationship introduced by Keeling (1961), where the isotope mass balance of an atmospheric water vapour sample collected in the mixed boundary layer above the crop canopy is described by two equations:

$$C_a = C_b + C_{ET} \quad (1)$$

$$\delta_a C_a = \delta_b C_b + \delta_{ET} C_{ET} \quad (2)$$

where C represents H_2O concentration (e.g. mmol H_2O mol^{-1} air); δ is the isotopic composition (‰) of H or O in water; and the subscripts a, b and ET refer respectively to the air sample, background atmosphere and ET source.

An atmospheric water vapour sample taken within the mixed boundary layer above the crop represents a mixture of isotopes and concentrations between the background atmosphere and the evaporating surface of the crop. These two equations can be combined and re-arranged to yield an equation that takes the form of a linear regression (Equation 3).

$$\delta_a = C_b (\delta_b - \delta_{ET})(1/C_a) + \delta_{ET} \quad (3)$$

A plot of the isotopic composition of water samples of the air (δ_a) in the mixed boundary layer on the y-axis against the reciprocal of the water concentration of the samples ($1/C_a$) on the x-axis yields a straight line with a slope of [$C_b(\delta_b - \delta_s)$] and an intercept of δ_{ET}, the isotopic composition of the ET flux. By knowing the isotopic signature of each of the ET sources, the direct soil evaporation and transpiration sources, the relative contributions of T and E to total ET can be separated at the field scale. This is done using a linear mixing equation:

$$T/ET = (\delta_{ET} - \delta_E)/(\delta_T - \delta_E) \quad (4)$$

where T/ET is the fractional contribution of plant T to total ET; δ_{ET} is the isotopic composition of the evapotranspiration; δ_E is the isotopic composition of soil E; and δ_T is the isotopic composition of T.

The method assumes leaf water to be at isotopic steady state. Water vapour δ^2H, $\delta^{18}O$ isotope composition and vapour concentrations at different heights were monitored using a stable isotopic water vapour analysis system. Soil sample at different depths and plant stem samples were also collected to measure their isotopic composition.

Isotopic mass balance of soil water

The IMB of soil water is described by the following relationships:

$$m_i + m_r = m_f + m_E + m_T \quad (5)$$

$$x_i\, d_i + x_r\, d_r = x_f\, d_f + x_E\, \delta_E + x_T\, d_T \quad (6)$$

where m is mass water; x is the fraction of the total mass of water in the system; δ is the isotope ratio value; and subscripts i, r, f, E and T denote the system components: i is the initial condition, r is rainfall or irrigation input, f is the final condition, E is the water evaporated from soil and T is the transpired water.

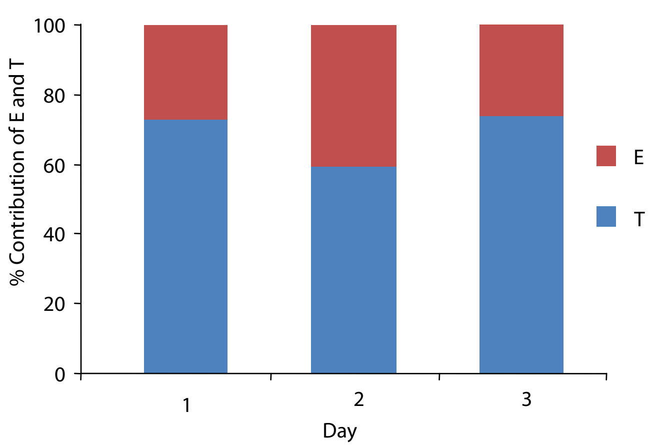
Equation 5 implies that the sum of the masses of initial water and water added as irrigation or rainfall is the same as the mass of water in the final condition plus the mass lost from E and T. The conservation of mass also applies to the isotope abundances in the system (Equation 6). The mass and isotope ratio of soil water in the initial and final conditions and in the irrigation and rainfall can be measured, and the isotope ratio of evaporated and transpired water can be calculated. The unknown quantities of mass of water transpired and evaporated are then solved. These relationships assume there is no lateral movement of water or beyond the observation zone, and that the isotopic composition of irrigation or rainfall is the same as that entering the soil water column, and roots do not fractionate soil water. The isotope composition of water evaporated from the soil (δ_E) can be calculated from the same equations shown above for estimating δ_E using the Keeling plot method, but must be integrated over the entire period of observation, from initial to final conditions.

TABLE 1. A summary of a selection of the studies carried out by the CRP participants

Country	Crop	Treatments	E & T methods	Experimental site
China (CAAS)	Winter wheat	Deficit irrigation (sprinkler) with 2 irrigations (75 and 45 mm)	Keeling plot $\delta^{18}O$, microlysimeter	Dryland farming and water-saving in Agriculture Station, Hengshui, Hebei
Morocco	Winter wheat	Flood	Keeling plot $\delta^{18}O$, AquaCrop model	Tensift catchment
Pakistan	Winter wheat	75%, 100% and 125% ETc and rainfed	Soil moisture neutron probe, AquaCrop model	NIAB Station, Faisalabad
Turkey	Winter wheat	Rainfed to full irrigation	Keeling plot $\delta^{18}O$	Saraykoy Research Station, Ankara-Mürted Basin
China (CAU)	Maize	Mulching (film and straw)	Isotopic mass balance $\delta^{18}O$	Beijing
Malawi	Maize	0, 50, 100, 150% ETc. 0, 50, 150 kg N/ha	Sap flow, isotopic mass balance $\delta^{18}O$	Southern Malawi
Vietnam	Coffee trees	Mulch vs no-mulch	Keeling plot $\delta^{18}O$	Dak Ha district, Tay Nguyen Plateau
Zambia	Paprika	50%, 75%, 100% & 125% ETc	Soil moisture using neutron probe	UNZA Field Station, Lusaka

TABLE 2. The ratio of soil evaporation to evapotranspiration (E:ET) for China CAAS studies

Crop	Sowing-Tillering	Tillering-Jointing	Jointing-Heading	Flowering-Grain filling	Grain filling-maturity	Total
Wheat	0.42	0.68	0.24	0.15	0.22	0.29



FUGURE 1. Proportion of E and T in winter wheat for three consecutive days in February 2012 in Morocco.

Other methods used such as the micro-lysimeter have been described in detail by Boast and Robertson (1982), Evett, Warrick and Matthias (1995) and Villalobos and Fereres (1990).

A selection of the studies carried out by the participants including the crop type, irrigation treatment, and E and T partitioning method is given in Table 1. Detailed methodologies and experimental designs of individual experiments are described in these proceedings. This presentation is grouped according to crop types: winter wheat, maize, coffee and paprika.

Briefly, for the winter wheat studies in the China CAAS experiment (Gong *et al*., 2013), winter wheat was grown under deficit irrigation with two irrigations (75 mm and 45 mm) applied in spring, and E and T were partitioned using Keeling plot and micro-lysimeter methods. In the Moroccan study (Amezou *et al*., 2013), water loss through E for winter wheat grown under flood irrigation was determined using the Keeling plot, validated using the AquaCrop model and total water loss for the growing season was determined from the AquaCrop model. In Pakistan, winter wheat was grown under different crop water requirement (ETc) conditions and E and T were separated using a soil moisture neutron probe and the AquaCrop model (Mahmood, Ishaque and Heng, 2013). In Turkey, winter wheat was grown under rain-fed to full irrigation and E and T were determined using the Keeling plot approach before and after irrigation (Kale *et al*., 2013).

In the case of maize, this was grown under conventional as well as under mulching (filming and straw residual) in China and the isotopic mass balance (IMB) method was used to determine E and T (Li *et al*., 2013). For Malawi, maize was grown under different crop water requirements and three nitrogen (N) fertilizer levels (0, 50 and 150 kg/ha). The IMB method was also used to partition E and T (Zingore, Fandika and Heng, 2013).

In Vietnam, E and T were determined using the Keeling plot method for a 10-year-old coffee plantation at different stages of the development cycle (mature, bean development, bean formation, flowering and bud development), as well as with and without crop residues (Dang *et al.*, 2013). The study was to investigate cultivation practices that could improve water use efficiency of coffee plants. In Zambia, E and T of the paprika crop was determined in the vegetative stage from soil moisture measured using the neutron probe (Phiri, Heng and Sinda, 2013).

RESULTS AND DISCUSSION

Winter wheat

In China, the proportion of soil E to the total water lost through ET is given in Table 2. The E/ET ratios early in the season were higher than that in the mid-season because of the smaller canopy cover. An average of 29 percent of total water was lost through soil E in this study.

In Morocco, the fractional contributions of soil E to total ET (E/ET) was measured in late spring under farmers' flood irrigation practice. Approximately 32 percent of the total ET was lost through soil E for three consecutive days in February 2012 (Figure 1). The results

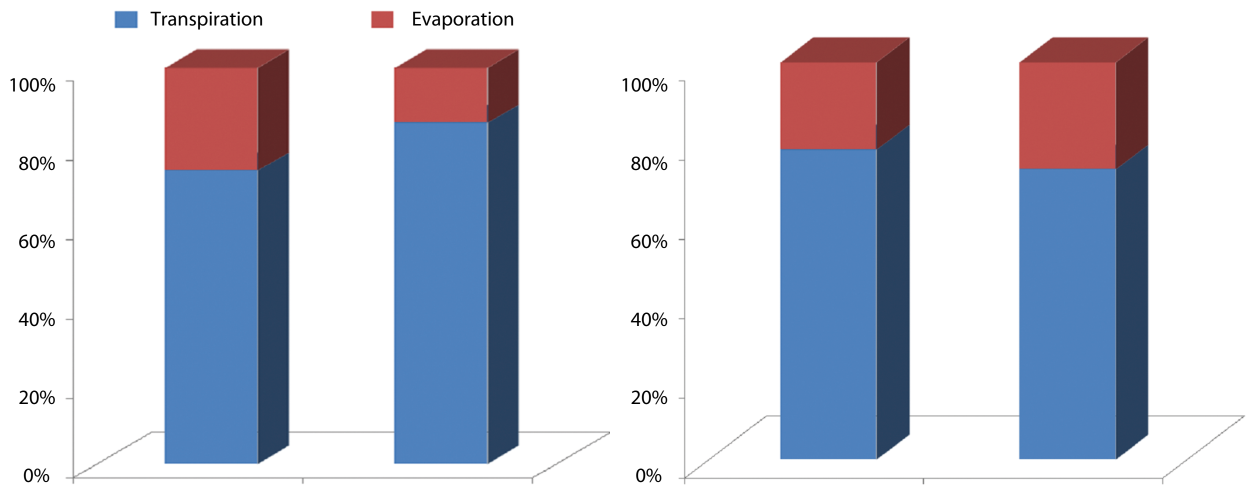


FIGURE 2. Comparison of E and T of winter wheat in Morocco for two days (22 and 24 Feb 2012) using the AquaCrop model (right) and isotopic (left) methods.

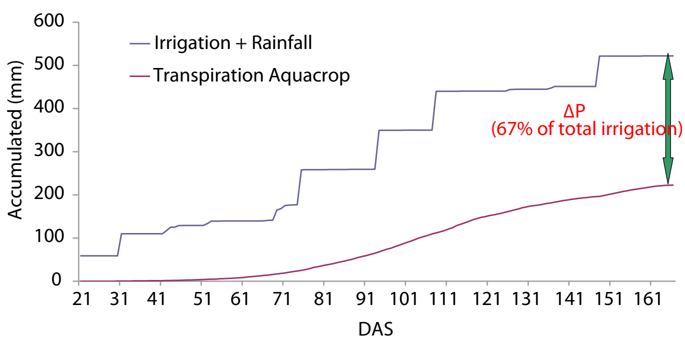


FIGURE 3. Cumulative T estimated by the Aquacrop model compared with total rainfall and irrigation in Morocco.

were compared with those simulated using the AquaCrop model (Figure 2). In order to investigate the efficiency of the irrigation practices which are representative of the practices in the region, seasonal water use was determined using the AquaCrop model. The analysis found that farmers' traditional visual observation of the need for irrigation from the physical condition of the crop is not efficient, a large quantity of the total water was lost through soil E and deep drainage ΔP (67 percent of total irrigation) (Figure 3).

Soil E was also the main component of water loss recorded in the Pakistan study under both rain-fed and irrigated treatments during the early growth stage due to the low canopy cover (Figure 4); however, in the irrigated treatment, after the fourth week, crop T increased and accounted for the majority of the total ET as canopy cover increased. Transpiration remained higher during the vegetative growth and flowering stages and started declining at grain filling. The initiation of leaf senescence during the grain filling stage resulted in a decrease in T with a corresponding increase in the E component. This was not the case in the rain-fed treatment where T remained low over most part of the season (Figure 4).

In Turkey, the proportion of T as percent of total ET was 70–96 percent before irrigation, while it was approximately 70 percent after irrigation, as determined from the Keeling plot analysis (Kale *et al.*, 2013).

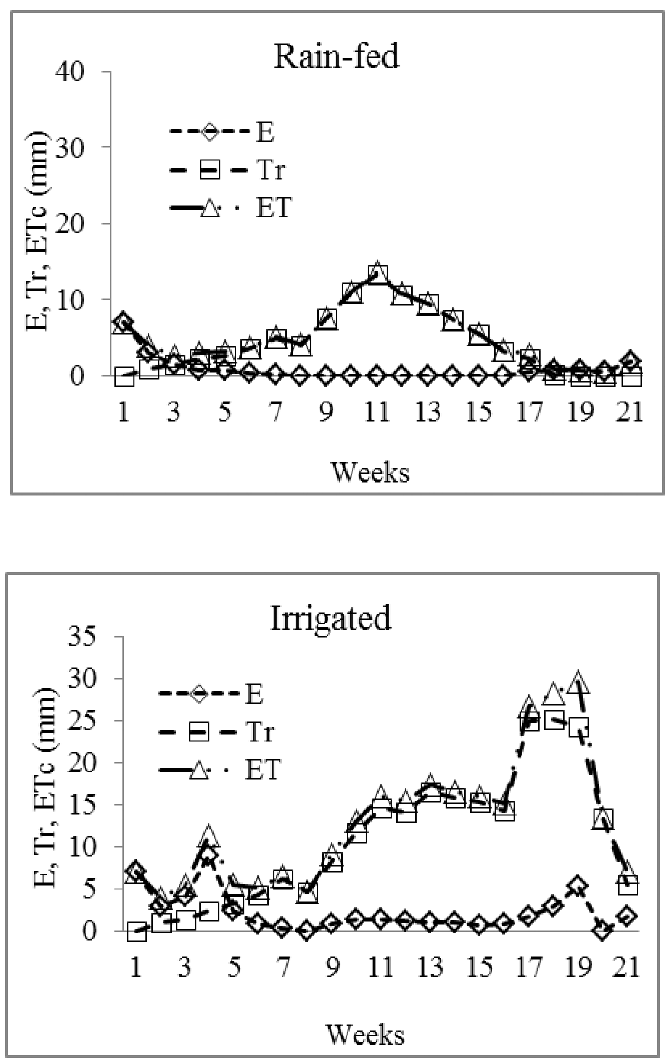


FIGURE 4. Pattern of wheat crop ET and its components under rain-fed and irrigated conditions in a Pakistan study as determined by the AquaCrop model (2010–2011).

TABLE 3. Partitioning E from ET of spring maize (values in mm) in China. Figures in brackets are percent of ET

Crop	Year	Conventional		Filming		Mulching		Bare	
		ET	E	ET	E	ET	E	ET	E
Spring maize	2010	206	63 (31)	157	22 (12)	178	43 (24)	182	65 (38)

Table 4. Partitioning the ET fluxes using the isotopic mass balance method for maize crop in Malawi

Treatment		
ET_C (%)	N (kg N/ha)	E/ET
50	50	0.92
	150	0.87
100	50	0.83
	150	0.80

Maize

In China, using the IMB method, the proportion of soil E was separated from total ET. The relatively high proportion of soil E for spring maize under the conventional method of planting (31 percent) compared with plastic filming and mulching with crop residues occurred mainly during May to June when the crop cover was lower with excessive rainfall events (Table 3). Both filming and straw mulching reduced E significantly in spring maize (by 19 percent and 7 percent, respectively) (Li *et al.*, 2013).

The proportion of T in the first 70 d of the maize crop season in Malawi constituted 43 percent for the two 100 percent ETc irrigation treatments and 36 percent for the 50 percent ETc irrigation treatment, based on the sap flow method. A simple isotope mass balance model was also used to determine the fractions of water lost through soil evaporation and crop transpiration for selected treatments. The relative contribution of evaporation (E/ET) during the first 50 d of the growing season was more than 83 percent for all treatments (Table 4).

Coffee trees

The contributions of the T and E components in the 10-year old coffee plantation showed that E was highest (53 percent) during the maturation and canopy forming stages, while during the budding and flowering stages and bean development it was the reverse, i.e. T was higher than E. However, in the budding and flowering stages following the bean development stage, which coincides with the dry season, the crop needs more water than at other stages. It is therefore vital to irrigate the crop to maintain soil moisture during the flowering period. The study showed that drip irrigation combined with mulching increased the T component of coffee plants by around 10 percent compared with the furrow and no-mulch practice.

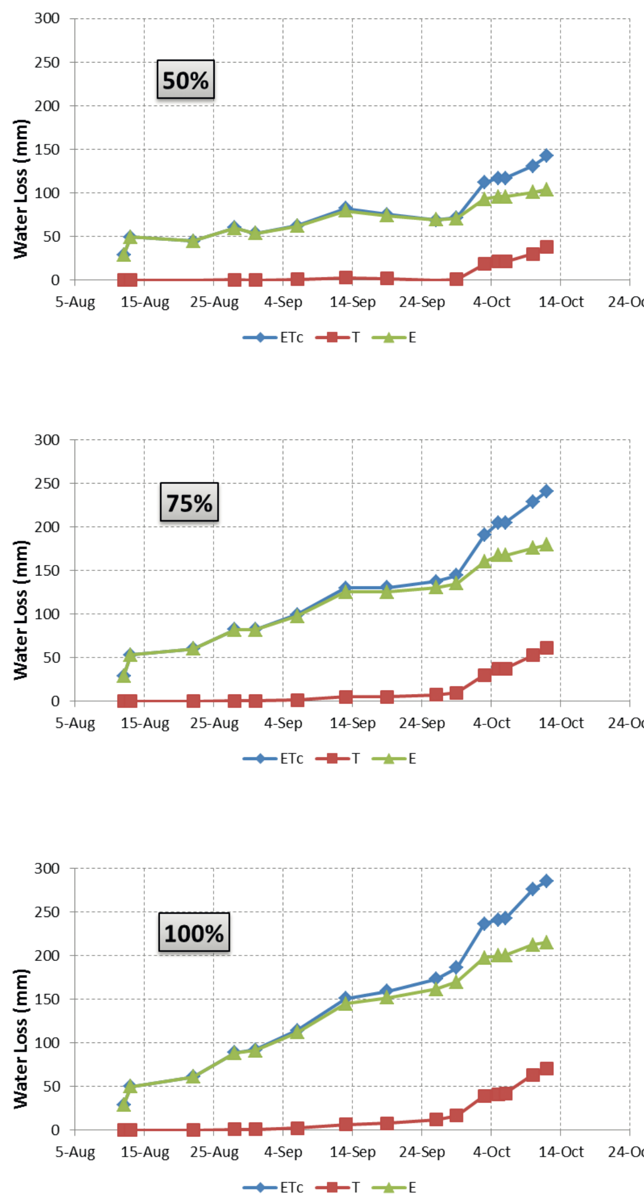


FIGURE 5. Cumulative water loss through E and T during the paprika vegetative period under 50, 75 and 100% ETc conditions.

TABLE 5. Percent of T and E of coffee plants before irrigation for the three important stages in a cropping season as determined by the isotopic technique

Stage	δ_{ET}‰	δ_E‰	δ_T‰	T%	E%
Mature and canopy reforming (September–November)	–11.6	–12.7	–10.4	47	53
Budding and flowering (December–February)	–9.7	–11.8	–10.5	85	15
Bean development (April–August)	–10.9	–13.8	–10.3	84	16

Table 6. T component of coffee plants in the flowering stage under different irrigation practices

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

TABLE 7. Partitioning of ETc 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%)

However, the T in the drip without mulch practice did not differ significantly from that of the traditional furrow and no-mulch practice. This was due to the fact that the leaf area index of the crop was as high as 6–7, and the tree canopies covered each other making solar radiation on the soil surface to be almost the same in the both cases.

Paprika

In Zambia, paprika was grown under 50, 75 and 100 percent ETc conditions. Water loss by soil E was calculated by subtracting T values from ET calculated from the root zone soil water balance. Generally, during the vegetative stage 75 percent of ET was lost as soil E (Figure 5). As crop growth progressed, the contribution of T started to increase. While the total amount of soil E was much higher under the 100 percent ETc treatment, the proportion of E to ET was almost the same under the three treatments (Table 7). In general about 75 percent of water was lost through soil evaporation.

CONCLUSIONS

The work conducted within the framework of this CRP showed that isotopic techniques ($\delta^{18}O$ or $\delta^{2}H$) using the Keeling Plot and the IMB method were able to provide improved estimates of soil E and T components. Together with the conventional method (e.g. the eddy covariance method), the transpiration percentage of a range of crop species in different environments was estimated. The transpiration efficiency of crops was generally lower in the African studies compared with those in Asia and Europe (China, Pakistan and Turkey) due to poorer soil fertility and irrigation management. This information allows appropriate soil and water management practices to be devised and implemented. Results from China and Pakistan showed that FAO's AquaCrop model provided the means to develop deficit irrigation schedules to save water while minimizing reductions in yield through saving unnecessary soil E and improving water use efficiency.

REFERENCES

Amenzou, N., Marah, H., Raibi, F., Ezzahar, J., Khabba, S., Lionel, J. & Ismaili, M. 2013. Isotopic and conventional techniques to improve the irrigation practice in order to enhance agriculture production under water limiting conditions in Morocco. *These Proceedings*.

Boast, C.W. & Robertson, T.M. 1982. A "micro-lysimeter" method for determining evaporation from bare soil: description and laboratory evaluation. *Soil Sci. Soc. Am J.* 46: 689–696.

Dang, D.N., Duong, H.S., Khuong, M.C., Heng, L.K. & Nguyen, M.L. 2013. Water use efficiency of coffee (Robusta) under mulch and drip irrigation on the Tay Nguyen Plateau, Viet Nam. *These Proceedings*.

Denmead, O.T., Dunin, F.X., Leuning, R. & Raupach, M.R. 1996. Measuring and modelling soil evaporation in wheat crops. *Phys. Chem. Earth,* 21: 97–100.

Evett, S.R.,Warrick, A.W. & Matthias, A.D. 1995. Wall material and capping effects on microlysimeter temperatures and evaporation. *Soil Sci. Soc. Am J.* 59: 329–336.

FAO. 2003. *Unlocking the water potential of agriculture*. Rome. (available at: *ftp://ftp.fao.org/agl/aglw/docs/unlocking_e.pdf).*

Ferretti, D.F., Pendall, E., Morgan, J.A., Nelson, J.A., LeCain, D.R. & Mosier, A.R. 2003. Partitioning evapotranspiration fluxes from a Colorado grassland using stable isotopes: seasonal variations and ecosystem implications of elevated atmospheric CO_2. *Plant Soil,* 254: 291–303.

Gong, D., Mei, X., Shi, J., Hao, W. & Heng, L. 2013. Partitioning wheat transpiration and soil evaporation with eddy covariance, stable isotope and micro-lysimeter in North China Plain. *These Proceedings.*

Hsieh, J.C.C., Chadwick, O.A., Kelly, E.F. & Savin, S.M. 1998. Oxygen isotopic composition of soil water: implications for partitioning evapotranspiration. *Geoderma,* 82: 269–293.

Jackson, N.A. & Wallace, J.S. 1999. Soil evaporation measurements in an agroforestry system in Kenya. *Agric. For. Meteorol*., 94: 203–215.

Kale, S., Sonmez, B., Madenoglu, S., Avag, K.I., Turker, U., Cayci, G. & Kutuk, C. 2013. 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. *These Proceedings.*

Keeling, C.D. 1961. The concentration and isotopic abundances of carbon dioxide and marine air. *Geochim. Cosmochim. Acta,* 24: 277–298.

Li, G., Hu, Q., Wang, X. & Li, B. 2013. Isotope mass balance method to partition evaporation from soil total water loss in winter and spring maize cropping systems in North China Plain. *These Proceedings.*

Mahmood, K., Ishaque, W. & Heng, L.K. 2013. Improving yield and water use efficiency of wheat (*Triticum aestivum* L.) by regulating plant-available water during crop development under semi-arid conditions in Pakistan. *These Proceedings.*

Moreira, M.Z., Sternberg, L.da S.L., Martinelli, L.A., Victoria, R.L., Barbosa, E.M., Bonates, L.C.M. & Nepstad, D.C. 1997. Contribution of transpiration to forest ambient vapour based on isotopic measurements. *Global Change Biol*., 3: 439–450.

Phiri, E., Heng, L. & Sinda, L.M. 2013. Evaluation of evapotranspiration and production of paprika (*Capsicum* Annum *L.*) using the soil water balance approach under variable irrigation water applications. *These Proceedings.*

Raes, D., Steduto, P., Hsiao, T.C. & Fereres, E. 2009. AquaCrop – The FAO crop model for predicting yield response to water: II. Main algorithms and software description. *Agron. J.,* 101: 438–447.

Steduto, P., Hsiao, T.C., Raes, D. & Fereres, E. 2009. AquaCrop – The FAO crop model to simulate yield response to water: I. Concepts and underlying principles, *Agron. J.,* 101: 426–437.

Villalobos, F.J. & Fereres, E. 1990. Evaporation measurements beneath corn, cotton and sunflower canopies. *Agron. J.,* 82:1153–1159.

Wang, X.F. & Yakir, D. 2000. Using stable isotopes of water in evapotranspiration studies. *Hydrol. Process.,* 14: 1407–1421.

Williams, D.G., Cable, W., Hultine, K., Hoedjes, J.C.B., Yepez, E.A., Simonneaux, V., Er-Raki, S., Boulet, G., de Bruin, H.A.R., Chehbouni, A., Hartogensis, O.K. & Timouk, F. 2004. Evapotranspiration components determined by stable isotope, sap flow and eddy covariance techniques. *Agric. For. Meteorol.,* 125: 241–258.

WWAP (World Water Assessment Programme). 2006. *Water: A shared Responsibility.* The United Nations World Water Development Report 2, UN Water.

Zingore, S., Fandika, I. & Heng, L.K. 2013. Enhancing water use efficiency in smallholder irrigation systems under water and nutrient limiting conditions. IAEA-TECDOC *(in preparation),* Vienna.

Evaluation of Evapotranspiration and Production of Paprika (*Capsicum Annum L.*) using the Soil Water Balance Approach under Variable Irrigation Water Applications

E. Phiri[1,*], L. Heng[2] and L.M. Sinda[1]

ABSTRACT

Precise estimation of evapotranspiration (ET) at the different growth stages is important for determining the field soil water balance and irrigation requirements. An experiment was conducted at the Research Field Station of the University of Zambia on a summer high value crop using a small-scale drip irrigation system. To maximize water use efficiency, the soil evaporation (E) and crop transpiration (T) components of the total ET were estimated for the cropping season. A randomized complete block design experiment with four replications and four irrigation water application rates based on crop water requirements (50 percent, 75 percent, 100 percent with and without plastic mulch), was carried out with paprika (*Capsicum Annum L.*) as a test crop. To determine T, soil water content was monitored with a soil moisture neutron probe to a depth of 150 cm over the season; green canopy cover was also monitored regularly using images taken with a digital camera. The results showed that T was negligible during the first 25 d after transplant (DAT) during plant establishment due to incomplete canopy cover and thereafter started to increase exponentially. The partitioning of ET into E and T using canopy cover values multiplied by ET showed that T estimates varied from 38 mm to 70 mm, depending on the treatments and resulted in an average value of 58.8 mm. Transpiration from the treatment with plastic mulch was 5 mm lower, with most of the water loss being through E during plant establishment before the plastic cover was installed. Generally, during the vegetative stage (the first 70 DAT) 75 percent of ET was in form of E while the remaining 25 percent was lost through T. The results on biomass production showed that the highest biomass production (421 kg/ha) was obtained in the 100 percent treatment while the lowest biomass (233 kg/ha) was in the 50 percent treatment; hence the higher the amount of water applied, the higher was the biomass produced. However, water use efficiency (biomass per unit ET) was highest under 50 percent ET and lowest in the 75 percent treatment (6 $kg \cdot ha^{-1} \cdot mm^{-1}$ versus 5.1 $kg \cdot ha^{-1} \cdot mm^{-1}$).

Key words: *water use efficiency, evaporation, transpiration, drip irrigation, paprika, biomass production.*

1 University of Zambia, School of Agricultural Sciences, Department of Soil Science, P. O. Box 32379, Lusaka, Zambia

2 International Atomic Energy Agency, Wagramerstrasse 5, PO Box 100, 1400 Vienna, Austria

* E-mail address of corresponding author: ephiri@unza.zm

INTRODUCTION

Low-head drip irrigation systems are being promoted for the production of high value crops to mitigate the impacts of drought in Southern Africa and 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 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 m^2) to keep the cost down and give room for incremental development not easily accomplished with normal commercial systems. Most smallholder farmers in Southern Africa and Zambia in particular rely heavily on rain-fed agriculture and are frequently faced with drought that affects their crop production. Against this background, a study was designed 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.) as a test crop under local conditions.

Evapotranspiration is the major component of the water balance in natural and managed ecosystems, accounting for more than 80 percent of precipitation inputs into ecosystems (Wilcox, Breshears and Seyfried, 2003). In water-limited ecosystems, partitioning of ET between plant transpiration (T) and soil evaporation (E) remain theoretical and technically challenging. In this study, the partitioning was achieved by multiplying the canopy cover values by ET to give the estimates of T. Water loss by E was then calculated by subtracting T values from ET values calculated from the root zone soil water balance. This study was part of a regional initiative to: (i) quantify and develop means to manage soil evaporative losses in ways that would 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.

Experimental design

The field experiment was conducted at the University of Zambia's Agriculture Field Station in Lusaka (lat: 15° 23″ S, long: 28° 20″ E alt: 1 262 m above sea level, asl). According to the Koeppen climate classification, the site has a warm temperate climate with dry winters and hot summers. The average daily maximum and minimum temperatures are 25°C and 15°C, respectively (Figure 1). The average rainfall varies from 800 mm to 1200 mm with an estimated precipita-

L.K. Heng, K. Sakadevan, G. Dercon and M.L. Nguyen (eds), Proceedings — International Symposium on Managing Soils for Food Security and Climate Change Adaptation and Mitigation. Food and Agriculture Organization of the United Nations, Rome, 2014: 331–336

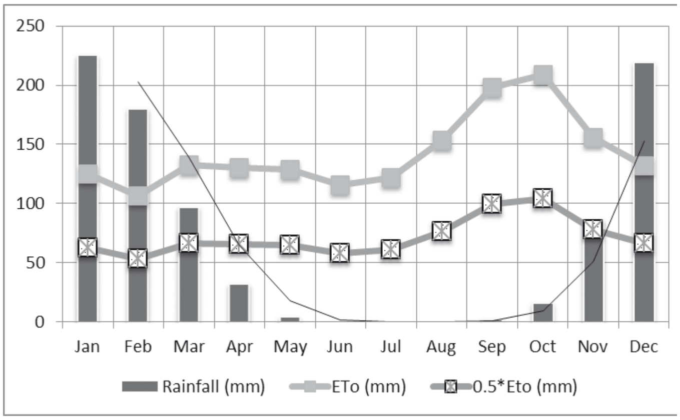


FIGURE 1. Long-term average monthly precipitation and evapotranspiration.

FIGURE 2. The drip system (left) and weather station (right) at the experimental site.

tion deficit of 647 mm per annum. The length of the rainy season is about 140 d (November–March), while the dry season is estimated at 225 d. 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.

The experimental design was a complete block design with four replicates and four treatments (water application rates of 50 percent, 75 percent, and 100 percent with and without plastic mulch) Water was supplied through a metered drip irrigation system. Each plot was equipped for measurements of (i) soil water profiles using a neutron moisture probe (CPN), (ii) water application through drip irrigation, (iii) biomass, and (iv) weather data monitored with an automatic weather station (Figures 2 and 3). Evapotranspiration was calculated using a root zone soil water balance approach and partitioned into E and T using estimates of crop green canopy from digital camera pictures.

Five-week-old seedlings were transplanted at an inter-row spacing of 0.90 m and 0.75 m between plants along drip lateral lines. During the early part of the season, from transplanting date until 37 d after transplanting (DAT), a portable sprinkler irrigation system was used twice (on 3 and 14 DAT) to apply 30 mm of water to ensure plant establishment. Afterwards, irrigation was applied every two days with a drip system; with one drip line every two rows and emitters 0.30 m apart. The plants received a basal fertilizer dressing at a rate of 300 kg/ha (N–P–K: 10–20–10) and a split top dressing fertilizer application of 300 kg/ha ammonium nitrate (NH_4NO_3). One week after transplanting (37 days after sowing, DAS), plants were subjected to a two-day interval irrigation schedule using a drip irrigation system with the exception of days when rainfall was received. Above ground biomass was estimated from measured plant girth diameter which was calibrated to biomass sampled four times during the experiment on 29 and 63 d after transplanting. Green canopy cover was determined from digital canopy pictures using Green Crop Tracker software (Liu and Pattey, 2010). After at least 48 hours in a ventilated oven at 70°C, the dry weight of the samples was determined separately for leaf, stem and fruit.

Soil type

The soil was 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 (USDA, 1998) (Table 1). The soil has a medium to low nutrient level (Table 2), hence fertilizer application was required for stabilizing and improving crop productivity.

Irrigation scheduling

The irrigation schedule was developed based on the historical weather data for the experimental site. The crop potential evapotranspiration (ETc) was estimated from the reference evapotranspiration (ETo) using the FAO-56 Penman-Monteith equation (FAO, 1998) corrected by the crop coefficient (Kc) for pepper.

Soil water measurements

For monitoring soil water content in the root zone, PVC pipe access tubes were installed in the centre drip line for measurements with a neutron moisture meter (CPN) at depth intervals of 0.15 m up to 1.50 m. The neutron moisture meter was calibrated in situ. In addition, soil water retention functions previously developed by desorption experiments from undisturbed core soil samples using standard techniques (Klute, 1986; Klute and Dirksen, 1986) were used to transform measured soil water profiles to measured hydraulic head profiles for drainage calculations for the root zone soil water balance. The Retention Curve Program for describing the hydraulic properties of unsaturated soils (van Genuchten, 1980; van Genuchten, Leij and Yates, 1991) was used to estimate soil hydraulic parameters from the moisture retention data. In addition, the gravimetric method was applied to measure soil water content at the beginning of the experiment and during the main growth stages.

TABLE 1. Soil physical properties

Soil depth (cm)	r_b (g/cm)	Sand (%)	Silt (%)	Clay (%)	Textural class (USDA)	FC (v/v)	WP (v/v)	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, r_b — bulk density

TABLE 2. Basic soil chemical properties in the top 20 cm soil depth

pH	Organic carbon (%)	Exch. Ca ($mg \cdot kg^{-1} \cdot soil$)	Exch. Mg ($mg \cdot kg^{-1} \cdot soil$)	Exch. K ($mg \cdot kg^{-1} \cdot soil$)	Available P ($mg \cdot kg^{-1} \cdot soil$)	Total soil nitrogen (%)
7.14	1.75	740	110	67.2	4.9	1.41

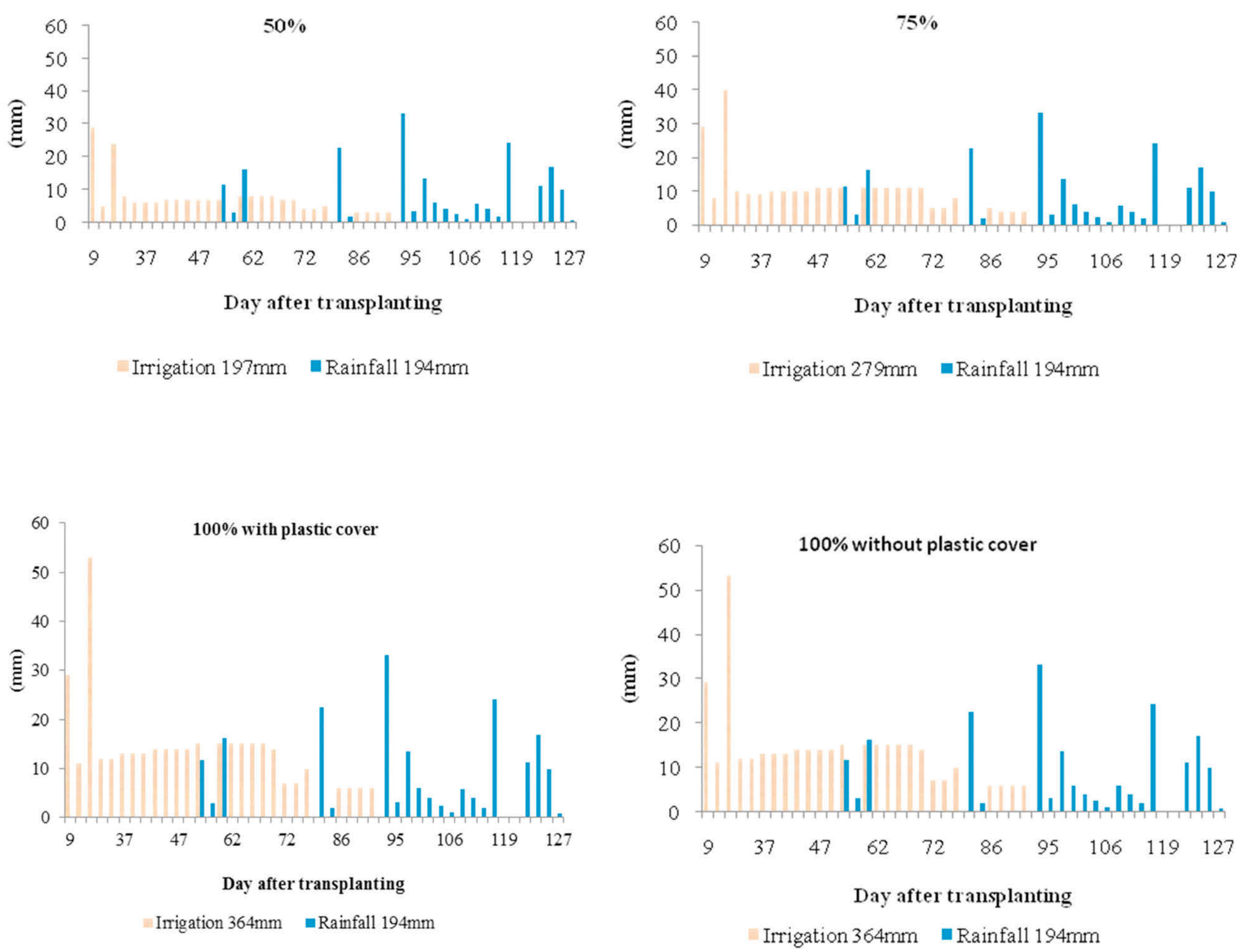


FIGURE 3. Total amount of water received through irrigation (yellow lines) and rainfall (blue lines) (2011–2012).

Root zone soil water balance

A root zone soil water balance for the paprika crop (Capsicum Annum L.), cultivar "Queen" was used to evaluate evapotranspiration. This approach to irrigation scheduling keeps track of the soil water deficit by accounting for all water additions and removals from the soil root zone. Crop water uptake or evapotranspiration accounts for the biggest (>90 percent) loss of water from the root zone while precipitation and irrigation provide the major additions. The classical water balance equation integrated over daily time periods ($\Delta t = t_{i+1} - t_i$) can be represented by:

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

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

Solving for the crop evapotranspiration, the above equation becomes:

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

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

$$Q = -K_{(v)} x \left.\frac{dH}{dz}\right|_z x \Delta t$$

where $K(q)$ = unsaturated hydraulic conductivity as a function of the volumetric water content; and (qv), H — hydraulic head, z — length and dH/dz — hydraulic head gradient.

The changes in root zone soil water storage (ΔS) during a given time interval ($\Delta t = t_2 - t_1$) were calculated from the integral of measured soil moisture profiles:

$$\Delta S_{(O,z)} = \int_{t_1}^{t_2} \int_0^z \theta dz$$

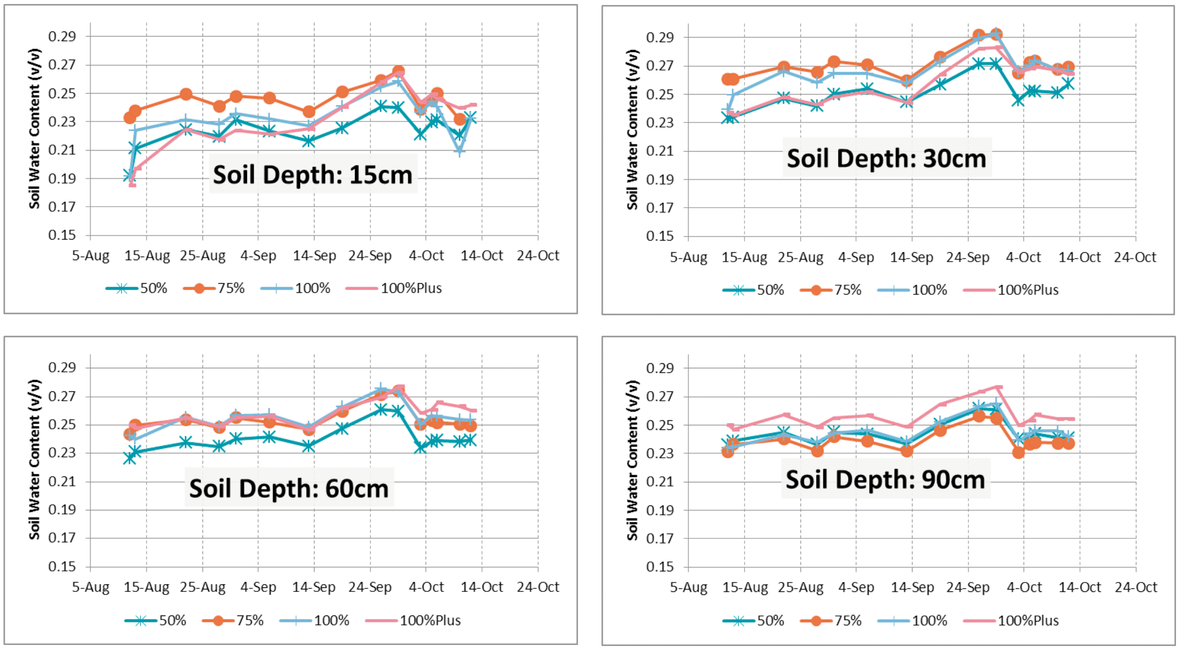


FIGURE 4. Effect of irrigation rate on soil moisture at selected soil depths.

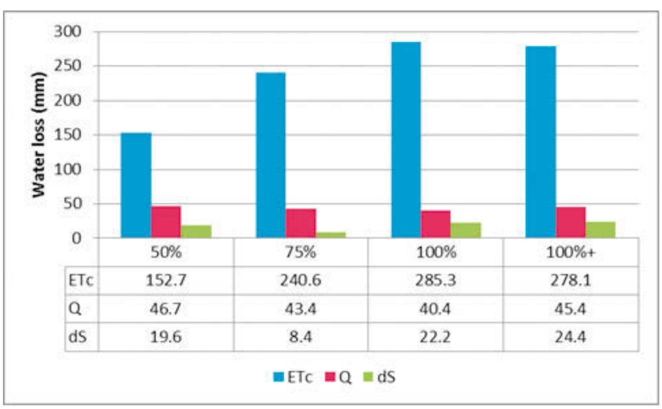


FIGURE 5. Components of the root zone water balance where ETc is crop ET (i.e. crop water uptake), Q is drainage below root zone and dS is the change in soil water storage.

Statistical analysis

The experiment was arranged in a completely randomized block design (CRBD) with four treatments and four replications. Data were analysed using GenStat and means were compared by the least square difference test (LSD) at five percent level of confidence.

RESULTS AND DISCUSSION

Weather data

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

The soil moisture at different soil depths over the cropping season affected by the rate of irrigation application is presented in Figure 4. No significant differences were recorded during the vegetative growth stage (first 70 DAT) of the crop. This may be attributed to the dominance of E during this period as the crop was becoming established. The general increase in soil water content in late September was due to the rainfall received, which to some extent cancelled treatment effects.

Generally the changes in soil water storage (DS) and drainage (Q) were positive, showing that treatments did lead to increases in soil water in the root zone (Figure 5). Results indicated that during the vegetative growth of the paprika crop, the water supplied to the root zone was partitioned into crop evapotranspiration (ETc) (78 percent), drainage (6 percent) and change in soil water storage (16 percent). No significant differences were observed between treatments and drainage and soil water storage changes except for ETc which was significantly ($p < 0.001$) lower in the 50 percent treatment compared with other treatments. The highest ETc was observed in the 100 percent treatment. The high ETc under the 100% + mulch (i.e. plastic cover) practice was predominantly E and occurred mainly during seedling establishment, i.e. before the plastic cover was placed on the soil surface. It was expected that E would be zero upon covering the surface with a plastic cover.

Crop green canopy cover and estimates of transpiration and evaporation

Digital pictures were taken fortnightly during the growing season and the data analyzed using the Green Crop Tracker software (Liu and Pattey, 2010) to estimate the percentage of green canopy cover which is an indication of the T component of crop evapotranspiration. The results presented in Figure 6 show that canopy cover was negligible during the first 25 d and thereafter increased exponentially.

Table 3 and Figure 7 show the results of the partitioning of ET into E and T during the first 70 d. The T estimates varied from 38 mm to 70 mm, with an average of 57 mm. When this is compared to the total water loss of 226 mm, T amounts to only 25 percent of total ET, implying that the majority of the added water (rainfall and irrigation) was lost through evaporation or deep drainage. The effect of mulching with plastic cover was also not significant, the T under

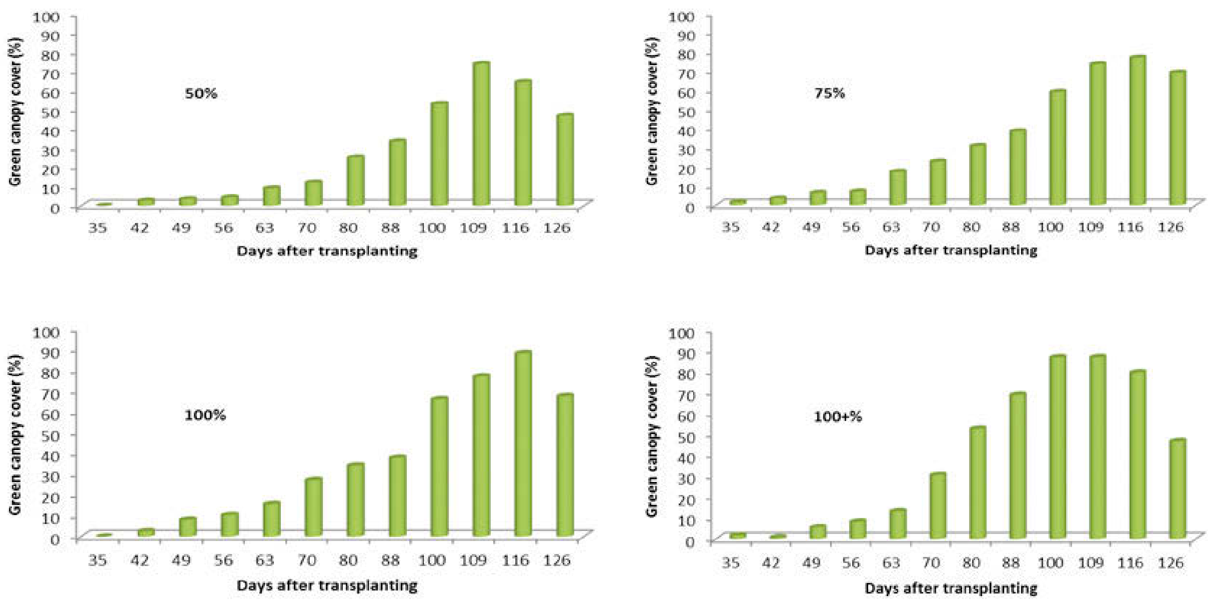


FIGURE 6. Green canopy cover of the four treatments.

TABLE 3. Partitioning of ETc (E + T), biomass production and water productivity during the vegetative stage

Treatment (% normal)	ETc (mm)	E (mm)	T (mm)	Biomass (kg/ha)	WP (ET) (kg·ha^{-1}·mm^{-1})	WP (T) (kg·ha^{-1}·mm^{-1})
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

ETc — evapotranspiration, E — evaporation, T — transpiration, WP — water productivity

plastic mulching was only 5 mm lower than without plastic as the plastic was installed after 70 DAT. The contribution of T started to increase after DAT 70 when vegetation cover increases to more than 80 percent of the total soil area.

Cumulative transpiration

Figure 8 presents the results obtained for the relationship between cumulative T and the applied water during the vegetative growth (within 70 DAT). The relationship is linear with no significant differences between the 75 percent and 100 percent treatments; however there were differences with the 50 percent treatment. The similarity between the two higher treatments may be because the plants were young and therefore unable to influence water loss through T. However, values for these levels were significantly higher than for the 50 percent treatment.

Biomass production

Results for biomass production measured during vegetative growth showed that biomass accumulated at a very low rate during the first 60 d of the growing season, and increased exponentially subsequently (Figure 9). The various irrigation treatments did not produce differences in biomass production until 60 DAP. The highest biomass was produced in the 100 percent water treatment, demonstrating the importance of water for biomass production and securing good yields.

CONCLUSIONS

This study has shown that during the vegetative growth stage of paprika, almost 78 percent of applied water was lost through ET, of which 75 percent was E and the remainder T. The water balance approach in combination with crop canopy cover analysis enabled partitioning of ET during the period studied, but whether similar levels of partitioning apply to all the growth stages requires further analysis.

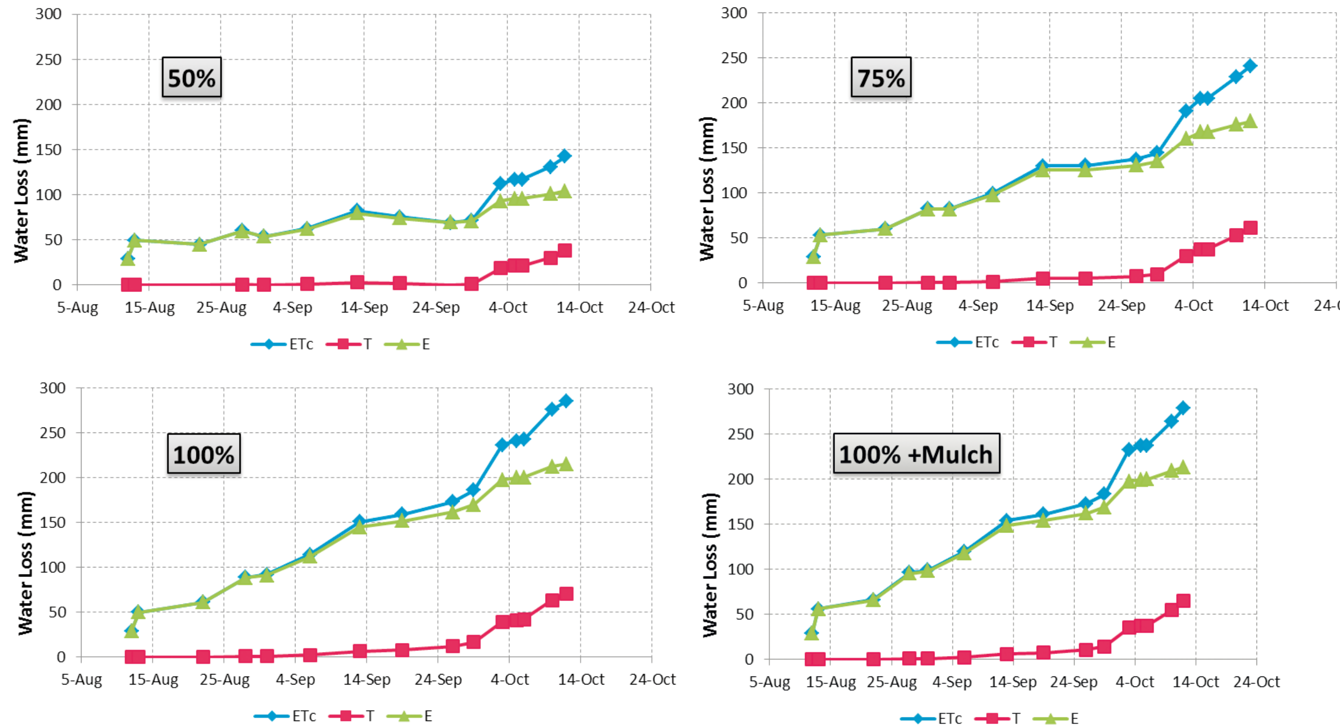


FIGURE 7. Partitioning of cumulative water loss through E and T during the vegetative period.

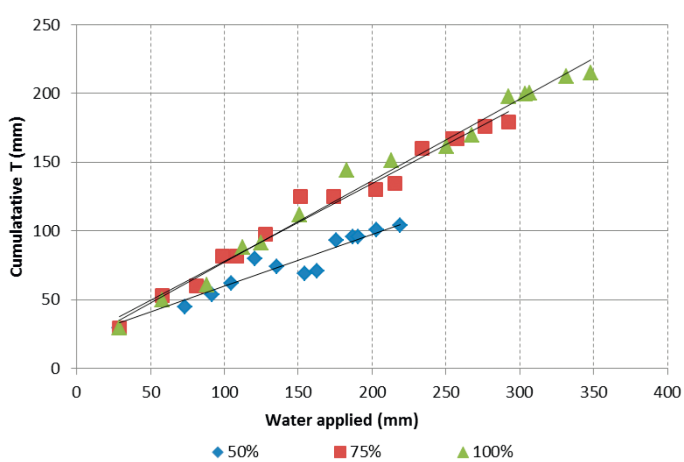


FIGURE 8. Relationship between cumulative T and applied water during vegetative growth.

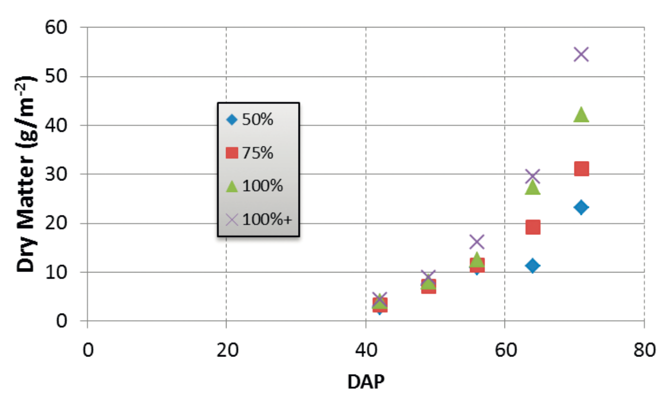


FIGURE 9. Biomass production during vegetative growth.

REFERENCES

FAO. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements, by R.G. Allen., L.S., Pereira, D. Raes & M. Smith. FAO Irrigation and Drainage Paper No. 56. Rome.

Klute, A. ed. 1986. Water retention: Laboratory methods. In Methods of soil analysis, Part 1: Physical and mineralogical methods, 2nd Edition, pp. 635–662. Madison, WI, American Society of Agronomy.

Klute, A. & Dirksen, C. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. In A. Klute, ed. Methods of soil analysis, Part 1: Physical and mineralogical methods, 2nd Edition, pp. 687–700. Madison, WI, American Society of Agronomy.

Liu, J. & Pattey, E. 2010. Retrieval of leaf area index from top-of-canopy digital photography over agricultural crops. Agric. Forest Meteorol., 150: 1485–1490.

United States Department of Agriculture. 1998. Keys to soil taxonomy, 8th Edition. Washington, DC, USDA-Natural Resources Conservation Service.

Van Genuchten, M.T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soil. Soil Sci. Soc. Am. J., 44: 892–898.

Van Genuchten, M., Leij, F.J. & Yates S.R. 1991. The RETC code for quantifying the hydraulic functions of unsaturated soils, pp. 4–41. Riverside, CA, U.S. Salinity Laboratory.

Wilcox, B.P., Breshears, D.D. & Seyfried, M.S. 2003. Water balance on rangelands. In T.A. Stewart & T.A. Howell, eds. Encyclopedia of water science, pp. 791–794. New York, Marcel Dekker.