Evapotranspiration partitioning components in an irrigated winter wheat field: A combined isotopic and micrometeorologic approach

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

Keywords— Evapotranspiration partitioning, stables isotopes, wheat, flood irrigation.

I. INTRODUCTION

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

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

Contrary to classic methods traditionally used, which remain insufficient (micro-lysimetry, sap flow) to determine correctly the evapotranspiration partition, the isotopic geochemical studies provides important information's to conclude this partition and to understand the extraction water processes by roots. Indeed, the heavy stables isotopes content increases in water soil by soil evaporation. On the other hand, the water extraction by the roots is without effect on this concentration. Water from growing-season precipitation is rapidly lost from the rooting zone by the transpiration or soil evaporation depending, in part, on the size of the precipitation event [3] and structural and physiological characteristics of the vegetation [4] the ratio of transpiration (T) to evapotranspiration (ET) is a synthetic parameter that integrates ecophysiological and micro environmental controls on total ecosystem water exchange [5].

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

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

II. MATERIALS AND METHODS

2.1 Study site

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

2.2 Meteorological data

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

2.3 Stable Isotopes Measurements

2.3.1 Soil water, plant water and vapor sampling

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

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

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

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

Where P_a is standard atmosphere pressure (about 1013.25 hP$_a$) and t = 1 (373.15/T$_a$).

2.3.2 Stable isotope and data analysis

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

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

Where *R*s and *R*st are the molar ratio of the heavy to light isotopes in the sample and the standard, respectively.

2.3.3 Theoretical overview

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

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

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

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

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

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

$$^{18}O\alpha* = [1.137(10^6 T^2) - 0.4156(10^3 T) - 2.0667] / 1000 + 1$$
$$D\alpha* = [24.844(10^6 T^2) - 76.248(10^3 T) - 52.612] / 1000 + 1 \quad (5)$$

Where, T is soil temperature recorded at 5 cm depth in degrees Kelvin.

ε_k is estimated using the diffusivity ratios of 1.0251 for H_2O: HDO and 1.0281 for $H_2O:H_2{}^{18}O$ [17].

The contribution of transpiration to evapotranspiration is estimated by Eq 6 [18]:

$$F_T = \frac{\delta_{ET} - \delta_E}{\delta_T - \delta_E} \quad (6)$$

III. RESULTS AND DISCUSSION

3.1 Evolution of climatic conditions

The temporal evolution of ET_0 is typically of a semi arid continental climate type. It is characterised by a high climatic demand. The lowest values of ET_0 (0.99mm/day) occurred during the winter and highest values occurred in the summer (9,89 mm/day) in this figure the evolution of ET_0 is similar to T mean of air. Precipitation temporal patterns over the growing season of citrus trees were characterized by low and irregular rainfall events, with a total precipitation amount of about 295 mm. The amount and timing of irrigations applied by the farmer are presented also in this figure (1)

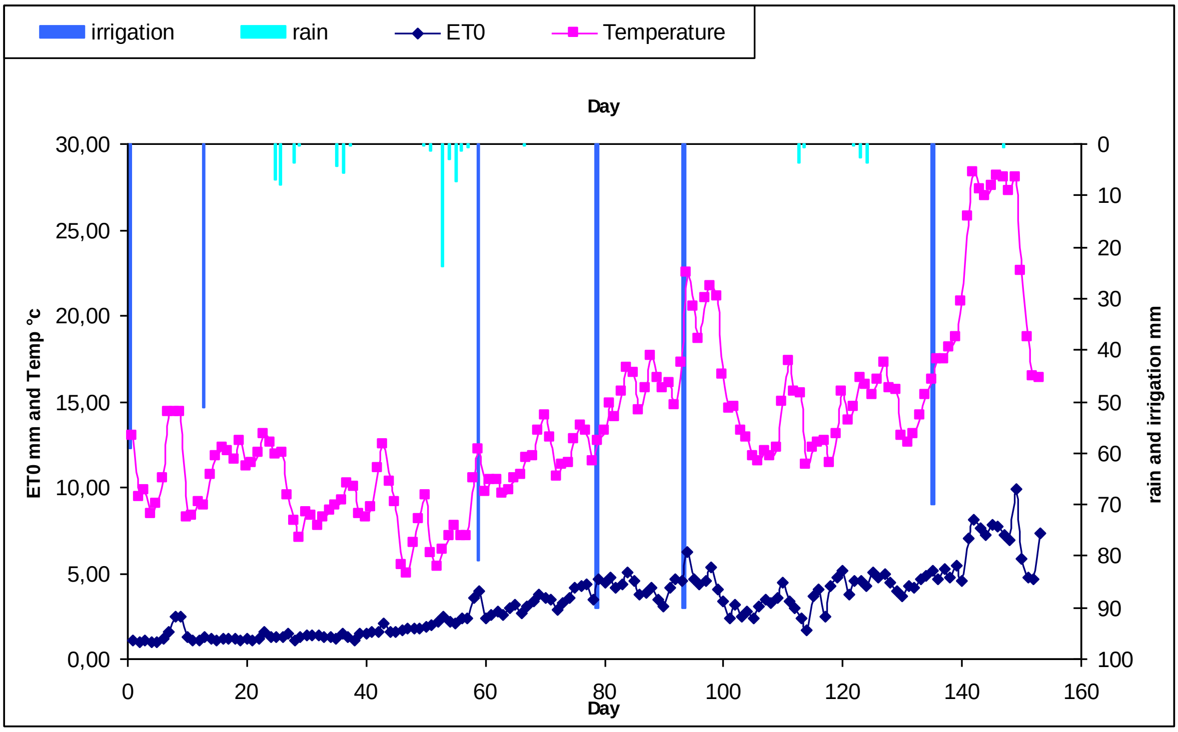

FIGURE 1: THE ENVIRONMENTAL CONDITION DURING THE GROWING SEASON

3.2 Partitioning Evapotranspiration components

3.2.1 The stable isotopic composition of vapor water, soil water and irrigation water

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

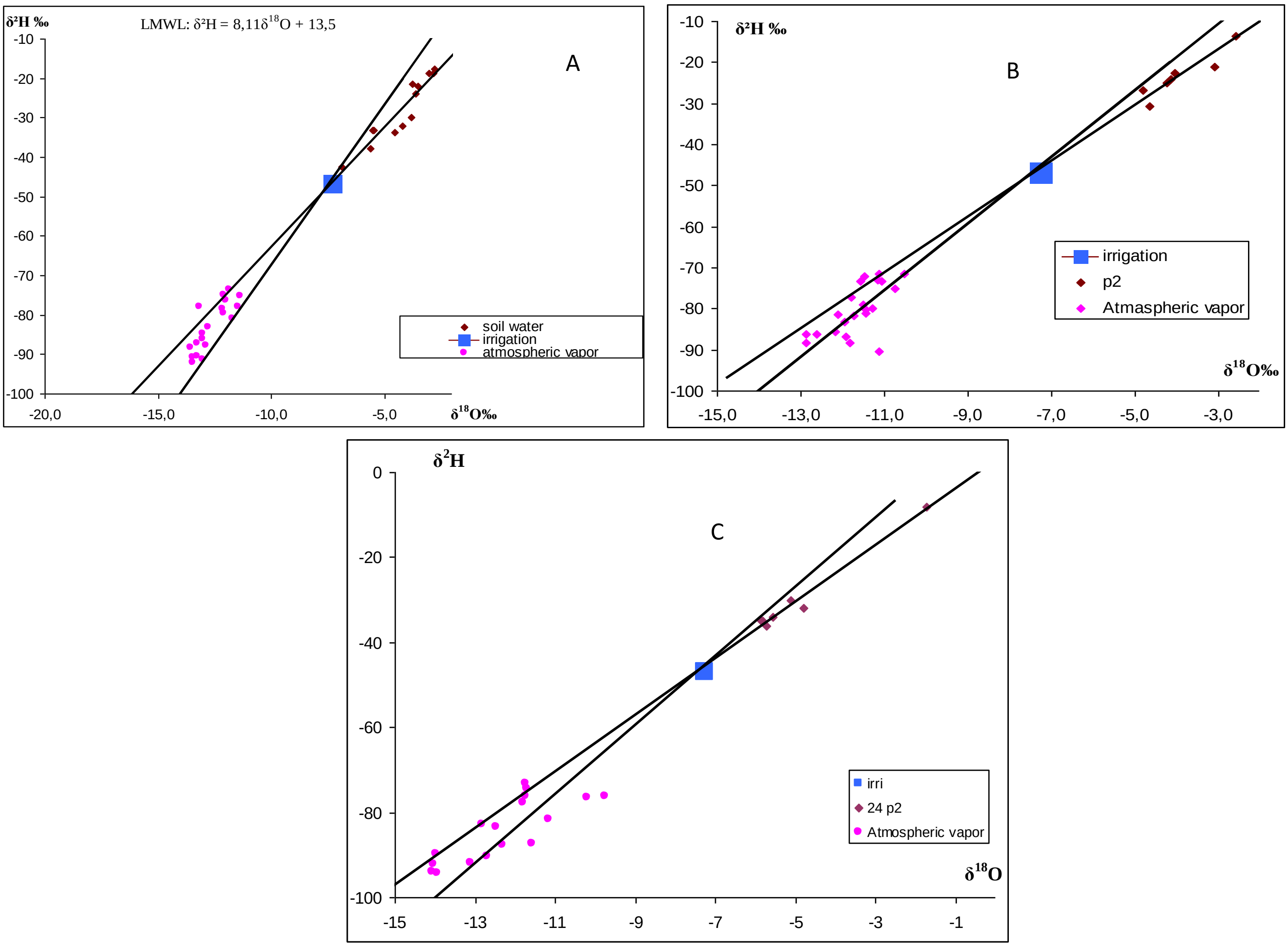

FIGURE 2 : δ^{18} *O* VERSUS *δD* IN ATMOSPHERIC WATER VAPOUR, IRRIGATION AND SOIL WATER AFTER OBSERVED AT WHEAT STUDY CASE *(A* 22 st, *B* 23 th and *C* 24 th February)

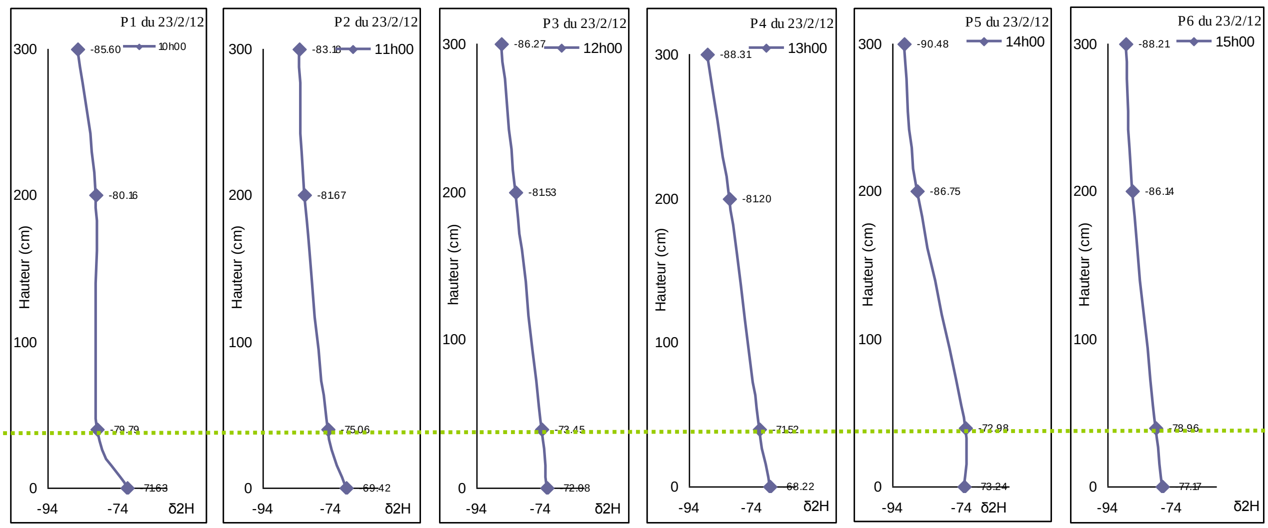

FIGURE 3 : EVOLUTION OF ISOTOPIC COMPOSITION *(δD)* OF ATMOSPHERIC VAPOR AT DIFFERENT LEVELS IN AND OUT VEGETATION *(B* 23 th February 2012)

3.2.2 keeling plot analysis

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

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

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

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

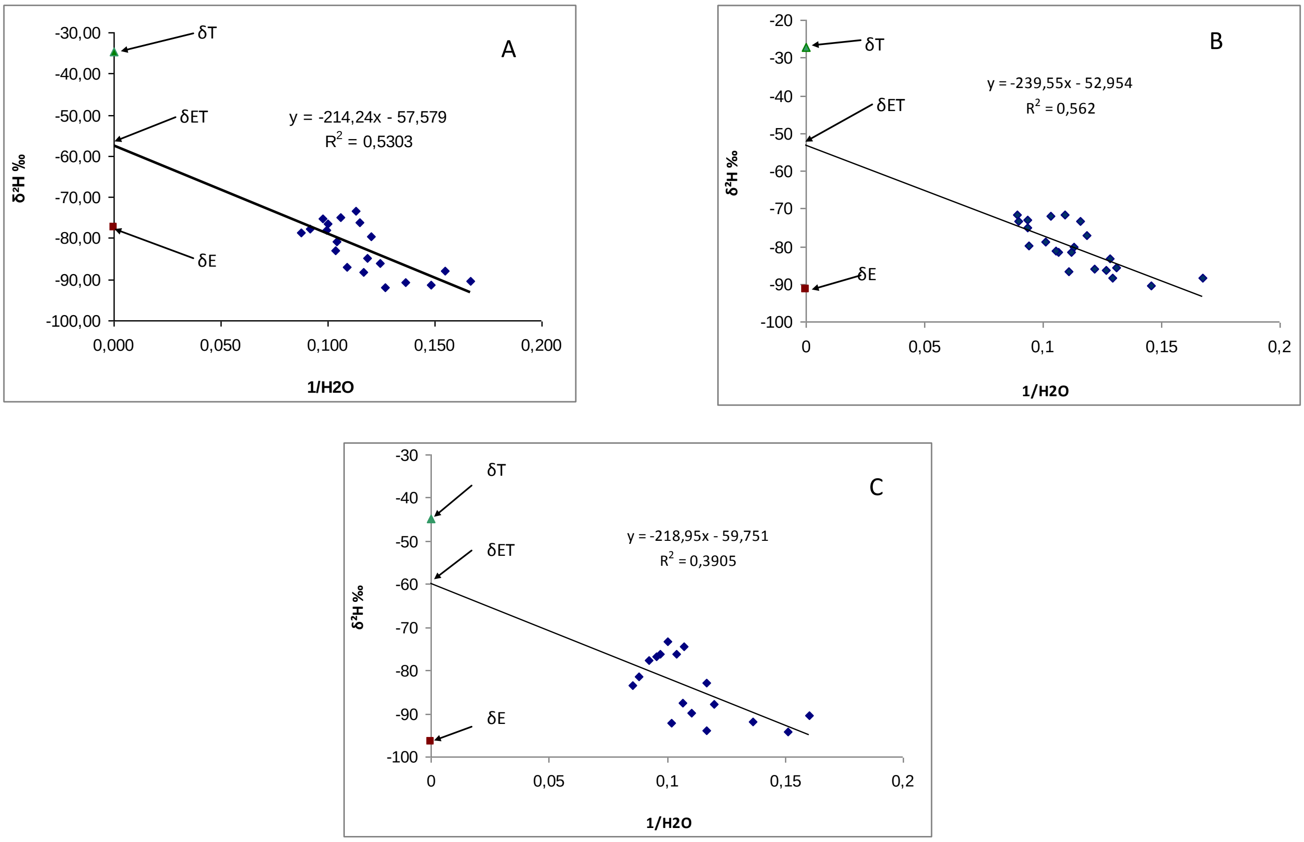

FIGURE 4 : RELATIONSHIP BETWEEN *δD* AND THE INVERSE OF THE AIR ABSOLUTE HUMIDITY AT DIFFERENT LEVELS ABOVE THE GROUND (*A* 22 st, *B* 23 th and *C* 24 th February)

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

	δs	δa	δT	δ ET	P	R^2	α	εk	δE	FT%
22/02/12	-27,26	-73,46	-34,55	-57,58	0,0002*	0,530	1,08	1,03	-119,28	0,73
23/02/12	-5,72	-68,22	-27,29	-52,95	0,0001*	0,562	1,08	1,03	-90,09	0,59
24/02/12	-26,05	-71,36	-37,44	-59,75	0,002*	0,39	1,08	1,03	-122,06	0,74

***The significance level is 0.05.**

3.2.3 Root water uptake depths

For the soil and stem water sampled at the same time, according to the mass balance of soil water and its isotopes, the proportions of each layer (f1–f4) can be determined by their isotopic signature and the isotopic signature of mixture (stem water).Eq 7

$$\delta Xt = f1\delta X1 + f2\delta X2 + f3\delta X3 + f4\delta X4 \quad (7)$$

$$\text{With: } 1 = f1 + f2 + f3 + f4$$

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

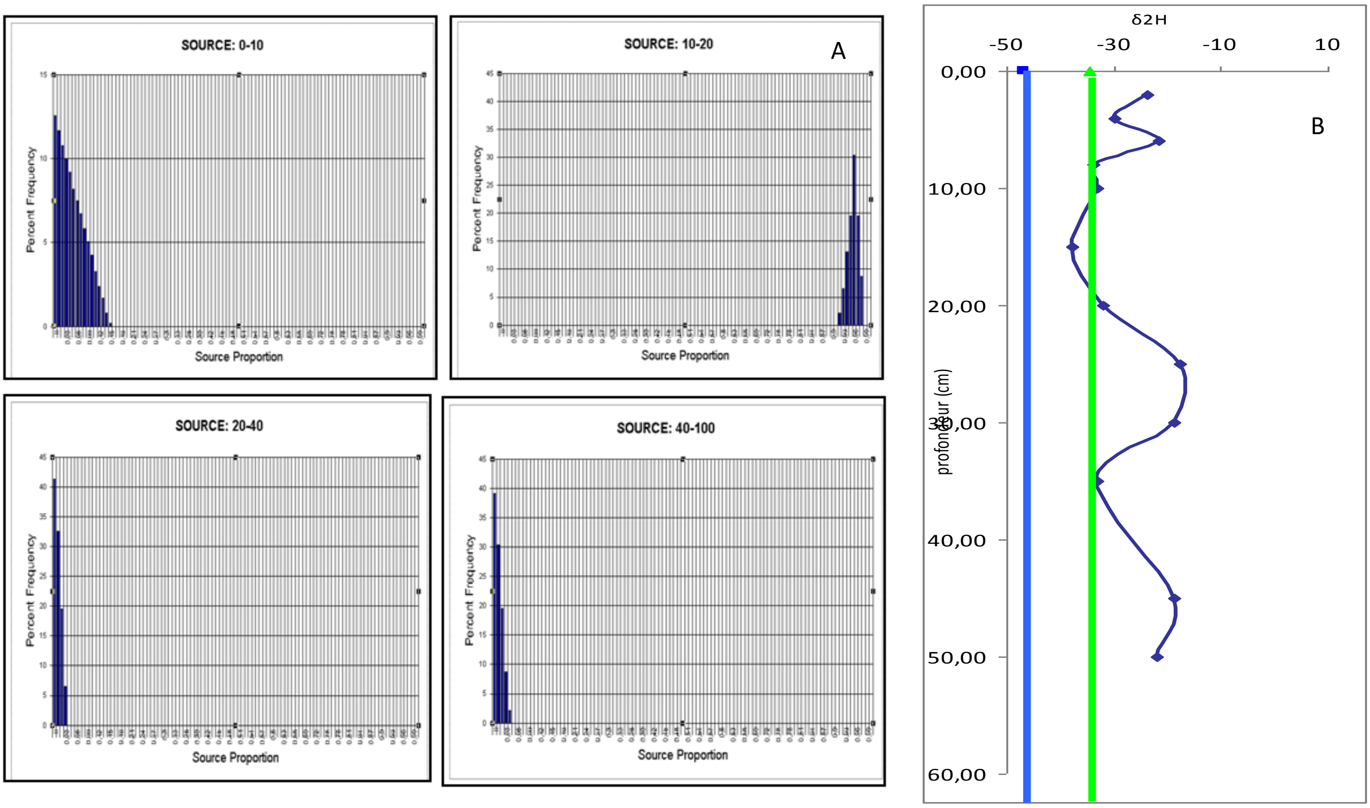

FIGURE 5 : HISTOGRAMS OBTAINED BY THE MULTI-SOURCE MASS BALANCE, WHICH SHOW THE ESTIMATED RANGES OF PROPORTIONAL CONTRIBUTION OF WATER FROM EACH SOIL DEPTH TO TOTAL WATER UPTAKE OF WINTER WHEAT (GREEN LINE STEM WATER, BLUE LINE IRRIGATION WATER)

The multiple-source mass balance assessment shows that the wheat absorbs the soil water from 10 cm to 20 cm (90%) at this growing stage (figure 5A)

Figure 5B show hydrogen isotope in the soil profile and corresponding crop stem. The isotopic profiles of soil water are determined by the evaporation effect and the antecedent precipitation and irrigation. Because soil was sampled when there was no rainfall several days before, the surface soil water was isotopically enriched due to evaporation. For other soil water, the isotopes were a mixture of evaporation effect and the isotopic signatures of antecedent precipitation and irrigation event.

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

IV. CONCLUSION

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

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

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REFERENCES

[1] El Mourid, M., Karrou.M., et El Gharous .M., 1996. la recherche en aridoculture respectueuse de l'environnement. Al Awamia. 92 : 69-81.
[2] Kirda, C., Moutonnet, P., Hera, C., Nielsen, D.R. (Eds.) (1999). Crop Yield Response to Deficit Irrigation. Kluwer Academic Publishers, Dordrecht, The Netherlands.
[3] Loik, M.E., Breshears, D.D., Lauenroth, W.K., Belnap, J., 2004. A multi-scale perspective of water pulses in dryland ecosystems: climatology and ecohydrology of the western USA. Oecologia 141: 181–269
[4] Huxman, T.E., Snyder, K.A., Tissue, D., Leffler, A.J., Ogle, K., Pockman, W.T., Sandquist, D.R., Potts, D., Schwinning, S., 2004. Precipitation pulses and carbon fluxes in semiarid and arid ecosystems. Oecologia 141: 254–268.
[5] Reynolds, J.F., Kemp, P.R., Tenhunen, J.D., 2000. Effects of long-term variability on evapotranspiration and soil water distribution in the Chihuahuan Desert: a modeling analysis. Plant Ecol. 150 : 45–159.
[6] Munnich, K., 1978. Soil water relationship, in : Proc. Symp. 'Study and Management of Water Resources in Arid and Semi-arid Regions', Ahmedabad, Inde, 1 er –4 mars 1978.
[7] Mathieu. R, Bariac. T., 1996. An isotopic study of water movements in clayed soils under a semiarid climate, Water Resour. Res. 32 : 779–789.
[8] Barnes. C.J. Allison G.B., 1983. The distribution of deuterium and 18 O in dry soils, J. Hydrol. 60 : 141–156.
[9] Van Dijk, A., Kohsiek, W., De Bruin, H.A.R., 2003. Oxygen sensitivity of krypton and lymann-a hygrometers. J. Atmos. Oceanic Technol. 20, 143–151.
[10] Ehleringer, J.R., J. Roden, and T.E. Dawson. 2000. Assessing ecosystem-level water relations through stable isotope ratio analysis. *In* O.E. Sala, R.B. Jackson, H.A. Mooney and R.W. Howarth (eds.), *Methods in Ecosystem Science. Springer, New York*, pp. 181-198.
[11] Helliker, B.R., J.S. Roden, C. Cook, and J.R. Ehleringer. 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.
[12] McRae, G.J. 1980. A simple procedure for calculating atmospheric water vapor concentration. *J. Air Pollution Control Association* 30: 394-396.
[13] Keeling, C.D., 1958. The concentration and isotopic abundance of atmospheric carbon dioxide in rural areas. Geochim. Cosmochim. Acta 13, 322–334.;
[14] Moreira, M.Z., L.daS.L. Sternberg, L.A. Martinelli, R.L. Victoria, E.M. Barbosa, L.C.M. Bonates, and D.C. Nepstad. 1997. Contribution of transpiration to forest ambient vapour based on isotopic measurements. *Global Change Biol*. 3: 439-450.
[15] Craig, H. and L.I. Gordon. 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. *Laboratory of Geology and Nuclear Science, Pisa,* pp. 9-130.

[16] Majoube, M. 1971. Fractionnement en oxygene-18 et en deuterium entre l'eau et sa vapeur. *Journal de Chimie Physique* 68: 1423-1436.
[17] Merlivat, Molecular diffusivities of H2 16O, HD16O, and H2 18O in gases, *Journal of Chemical Physics* 69 (1978) 2864–2871.
[18] Yakir, D. and L.D.S.L. Sternberg. 2000. The use of stable isotopes to study ecosystem gas exchange. *Oecologia* 123: 297-311.
[19] 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.
[20] Yucui Zhang,Yanjun Shen, ,Hongyong Sun ,John B.Gates. 2011. Evapotranspiration and its partitioning in an irrigated winter wheat .eld:A combined isotopic and micrometeorologic approach. Journal of Hydrology 408 (2011)203 –211.
[21] Brunel,J.P.,Walker,G.R.,Dighton,J.C.,Monteny,B.,1997.Use of stable isotopes of water to determine the origin of water used by the vegetation and to partition evapotranspiration.A case study from HAPEX-Sahel.J.Hydrol.189,466 –481.
[22] Ferretti,D.F.,Pendall,E.,Morgan,J.A.,Nelson,J.A.,Lecain,D.,Mosier,A.R.,2003. Partitioning evapotranspiration .uxes from a Colorado grassland using stable isotopes:seasonal variations and ecosystem implications of elevated atomspheric CO2.Plant Soil 254,291 –303.
[23] Hsieh,J.C.,Chadwick,O.A.,Kelly,E.F.,Savin,S.M.,1998.Oxygen isotopic composition of soil water:quantifying evaporation and transpiration.Geoderma 82, 269 –293.
[24] Phillips, D.L., Gregg, J.W., 2003. Source partitioning using stable isotopes: coping with too many sources. *Oecologia* 136, 261–269.