

Research Paper

Estimation of soil evaporation and infiltration losses using stables isotopes, Fluxmeter and Eddy-Covariance system for citrus orchards in a semi-arid region (Morocco).

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ABSTRACT

In arid and semi-arid regions water scarcity is one of the main limiting factors for economic growth. In the context, an experimental setup was conceived to monitor seasonal water consumption of citrus plant irrigated by drip irrigation system in Agafay station, middle of Morocco. For that, an Eddy-Covariance system, meteorological station, fluxmeter, as well as measurements of soil moisture and temperature were continuously operated during experimentation. The stable isotope was used to partition Evapotranspiration (ET) components. By using the water balance equation, the results showed that about 37% of total irrigation and rainfall is lost by infiltration and runoff. Additionally, the partitioning of evapotranspiration using the stable isotope showed that soil evaporation is very small compared to the transpiration at least during tow sampling days. This result confirms that the irrigation method applied by the farmer was very appropriate for the orchard but it is necessary to re-examine amount of water applied and timing of irrigation in order to minimise the loss by infiltration

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INTRODUCTION

The arid and semi-arid regions constitute roughly one third of the total earth surface (Amiran, 1966). 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 (Chehbouni et al., 2008). Therefore, there is a great need to rationalize this use, and thus to monitor more closely the water resources. Amongst the fluxes that the different actors of the water sector need to assess, soil evaporation and infiltration are of major importance. The quantification of infiltration can be determined directly by using the fluxmeters. However, this method gives only local measurements. At field scale that interests the farmer, one can use the Eddy Covariance method combined with the

measurements of rainfall and the quantity of irrigation water. Ezzahar et al. (2007) have evaluated this method over an olive orchard under furrow irrigation which creates a big heterogeneity in terms of soil moisture and they revealed that the sum of infiltration and runoff represents 41% of the total irrigation. At a homogenous scale, the combining of both techniques (that is Eddy covariance and fluxmeters) can offer the possibility to determine separately the infiltration and runoff quantities. In addition to the infiltration and runoff terms, the measurement of soil evaporation is a crucial need especially in semi-arid region where the potential evaporation is very high, greatly exceeding the annual rainfall. The determination of this parameter is not an easy task especially over tall and sparse vegetation where the water transport is very complicated

compared to the short vegetation. Due to the technical constraints related to other micrometeorological techniques such as Eddy Covariance, stable isotopic tracer methods offer a new opportunity to study the components of evapotranspiration (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.

MATERIALS AND METHODS

2-1 Study Site

The study site was conducted within an orchard of the mandarin (Afourar variety) 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 with an annual average of about 240 mm against a higher reference evapotranspiration ($ET_0=1600$ mm/year). The trees were planted in a regular square pattern (4 × 6 m). The crop was 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% clay, 32% silt and 50% 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., 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 moisture. Measurements were taken at 1 Hz, and averages stored at 30 min intervals on CR23X data loggers (Campbell Scientific Ltd.).

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 (ET). The EC system used, consist of commercially available instrumentation: a 3D sonic anemometer (CSAT3, Campbell Scientific Ltd.) and a fast response hygrometers (Campbell

Scientific Inc., USA). Raw data were sampled at a rate of 20 Hz and were recorded using CR5000 data loggers (Campbell Scientific Ltd.). The half-hourly fluxes were later calculated off-line using Eddy Covariance processing software 'ECpack', after performing all required corrections for planar fit correction, humidity and oxygen (KH₂O), frequency response for slow apparatus, and path length integration (Van Dijk et al., 2004).

Fluxmeter measurements

Besides the standard meteorological measurements, one fluxmeter is installed at 80 cm depth which corresponds to the root zone in order to quantify the water loss by deep percolation.

Stable isotopes measurements

Soil water, plant water and vapor collection

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.

Water vapor was collected from 5 heights at a time (0.1, 1.75, 2.95, 4.45 and 8.12 m). During the collection period mentioned above, sampling started at 10:00, 11:00, 13:00, 14:00 and 15:00 h. For each group vapour was collected during 1 h 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 (Helliker et al., 2002) 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 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, 5 probes of model HMP45AC (Vaisala Oyj, Helsinki, Finland) for measuring the air temperature (T_a , in Kelvin) and relative humidity (h ,) every 5 min was mounted. Using T_a , h and atmospheric pressure (P_a , in hPa), water vapor concentration was calculated by: Equation 1 (McRae, 1980) :

$$H_2O(mm\text{mol}\text{mol}^{-1}) = \frac{10h[P_a \exp(13.3185/t - 1.9760/t^2 - 0.6445/t^3 - 0.1299/t^4)]}{P_a} \quad \text{Eqn 1}$$

Where: P_a is standard atmosphere pressure (about 1013.25 hPa) and $t = 1 - (373.15/T_a)$.

Using the inverse of average vapour concentration ($1/[H_2O]$)

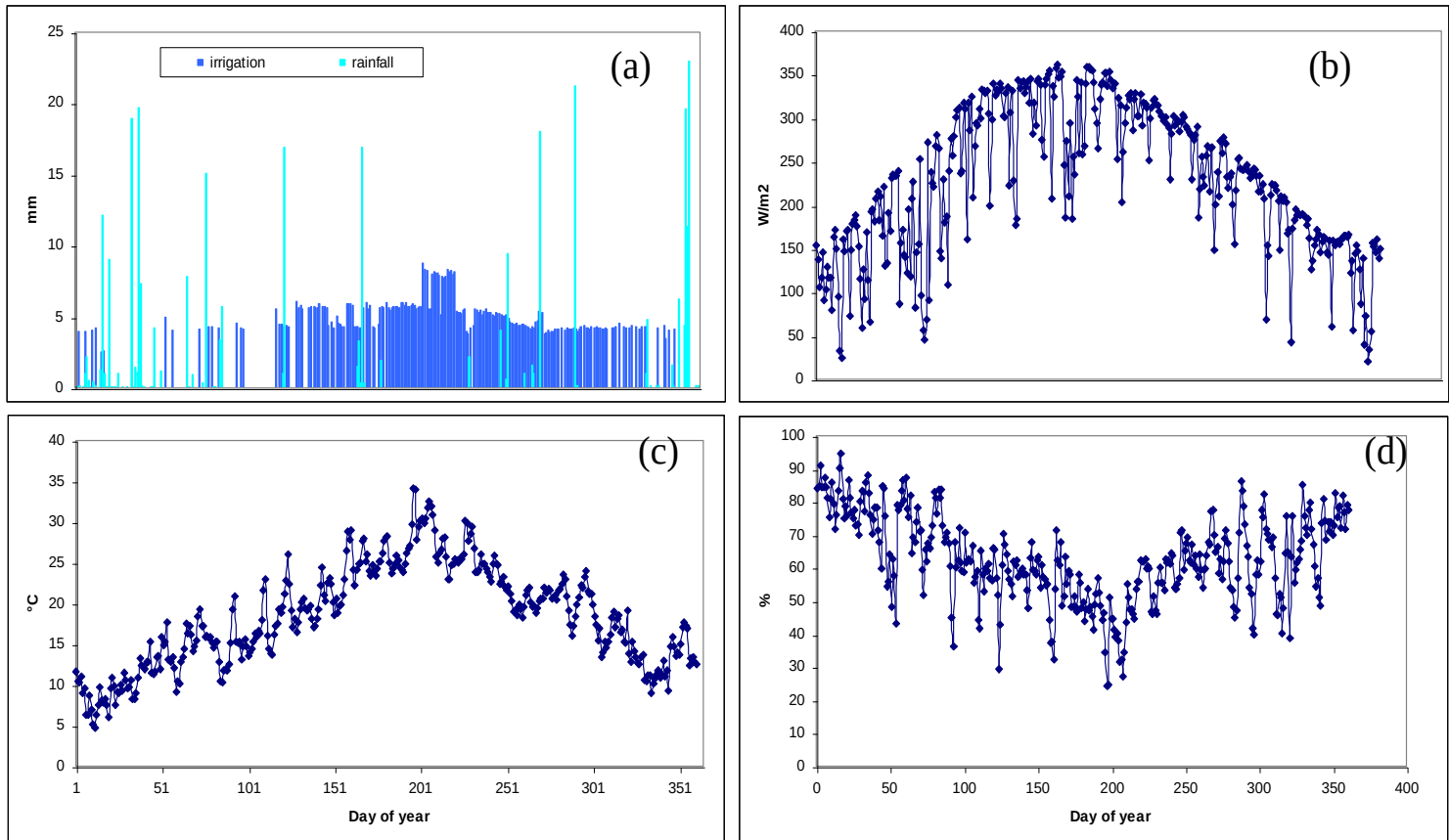


Figure 1. The variation of the environmental conditions during the growing season of the year 2009. (a; precipitation and irrigation, b; solar radiation, c; temperature, d; humidity)

during sampling period of each height as independent variables, and isotopic values of water vapor ($\delta^{18}\text{O}$ or δD) collected at the corresponding height as dependent variables, the Keeling plots were generated.

Stable isotope and data analysis

In the laboratory, Soil and plant water was extracted by cryogenic vacuum distillation (Ehleringer et al., 2000). The water samples were isotopically analyzed at National Center of Sciences and Nuclear techniques (CNESTEN) using a spectrometer laser DLT-100 (± 1 standard deviation). The standard deviations for repeated analysis of laboratory standards were 0.2 and 1‰ for ^{18}O and D respectively. Concentrations of these isotopes are expressed as deviation from an international standard (V-SMOW) and using δ notation in per mil (‰): Equation 2

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

Where R_s and R_{st} are the molar ratio of the heavy to light isotopes in the sample and the standard, respectively.

RESULTS AND DISCUSSION

Evolution of climatic conditions

Figure 1 presents the variation of climatic data during growing season of 2009, including global radiation (R_g), temperature (T_a), humidity (H_r) of the air and rainfall. The lowest values of T_a occurred during the winter (4.4°C) and the highest values occurred in summer (43.5°C). Atmospheric humidity is low (56%) while global radiation was high in summer (606 W/m^2) but low in winter (35 W/m^2). The rain is characterized by an important irregularity through this year.

Using these climatic data, Er-Raki et al. (2012) have reported that the reference evapotranspiration ET_0 pattern is characterized of semi-arid continental climates, with an average accumulated annual ET_0 of 1355 mm. The lowest values of ET_0 occurred during the winter and autumn (0.05 mm/day) and the highest values occurred in the summer (11.07 mm/day).

Flux data quality assessment

The energy balance closure is an important indicator of the

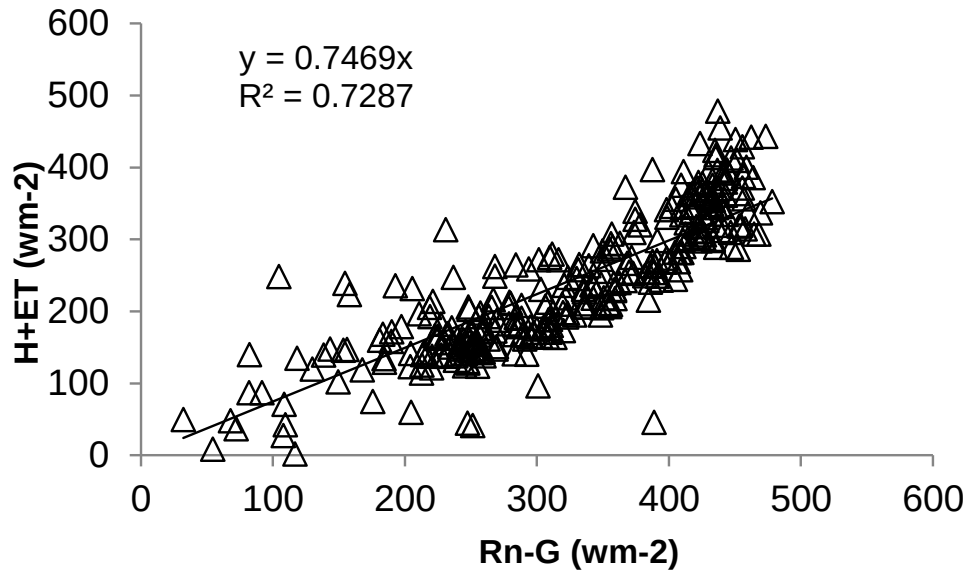


Figure 2. Daily energy balance closure, H : sensible heat flux, ET: latent heat flux, Rn: net radiation, G :soil heat flux.

performance of an Eddy Covariance system. By assuming the principle of conservation of energy, the energy balance closure is defined as $Rn-H-ET-G$ and should be close to zero (Rn is net radiation, G is soil heat flux, and H and ET are the sensible and latent heat fluxes derived from the Eddy Covariance). Figure 2 presents a cross plot between measured ($Rn-G$) and the sum of the turbulent fluxes ($H+ET$). The difference in terms of the sources areas of the different instruments has the biggest impact on the closure of the energy balance especially over sparsely vegetated surfaces. The source area sampled by eddy covariance 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, comparatively to what has been reported in literature, the closure can be considered as fairly acceptable.

Loss by infiltration

In this current study, the infiltration losses are evaluated by using two methods: an indirect method based on the water balance equation and direct one by fluxmeter.

Water balance method

This method consists of comparing the cumulative evapotranspiration measured by Eddy covariance system and the sum cumulative amount of irrigation and rainfall. Total rainfall during the experiment was 295 mm, while the average annual in the Tensift river basin is 240 mm. Figure 3 shows that lost by infiltration and runoff during this season is about 427 mm that represents 37% of sum

irrigation and rainfall. Ezzahar et al. (2007) have evaluated this method over an olive orchard under furrow irrigation which creates a big heterogeneity in terms of soil moisture and they revealed that the sum of infiltration and runoff represents 41% of the total irrigation.

Fluxmeter measurements

This method entails measuring directly only infiltration by the fluxmeter. The variation of the cumulative infiltration and sum cumulative amount irrigation and rain (Figure 4) shows that the lost by infiltration is about 425 mm, that represents 32% 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 of rain. This result confirms the obtained result using the water balance equation. The result revealed that the farmer applied a large amount of water. So it is necessary to re-examine amount of water applied and timing of irrigation.

Partitioning evapotranspiration components

The stable isotopic composition of water vapor, stem water 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 -6.194‰ to -5.273‰ for $\delta^{18}O$, and from -45.24.7‰ to -43.47.0‰ for δD . Isotopic compositions of vapor (δ_a) ranged from -11.317.9‰ to -7.815‰ for $\delta^{18}O$, and from -

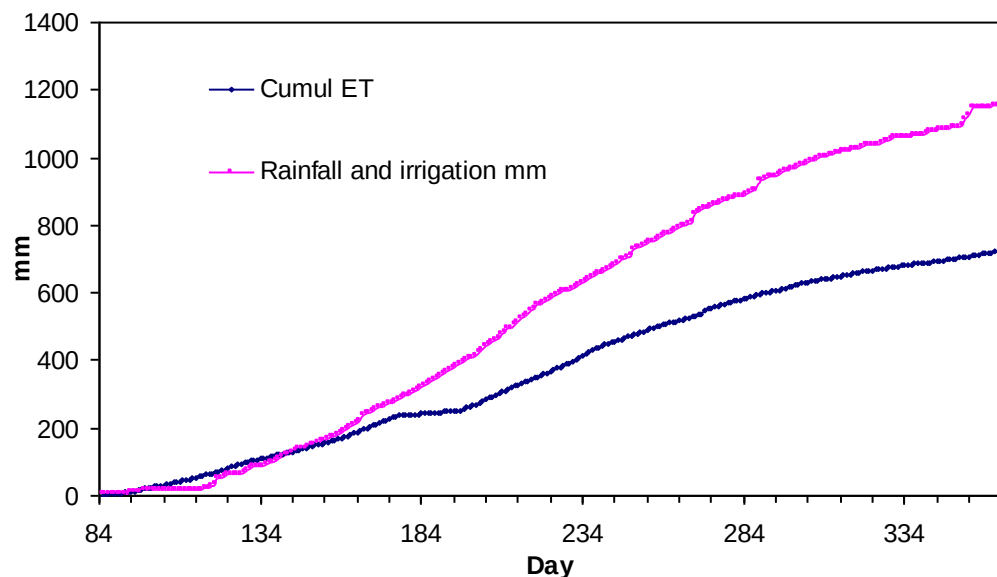


Figure 3. Cumulative Evapotranspiration (ET) compared to sum precipitation (mm) and irrigation amount (mm)

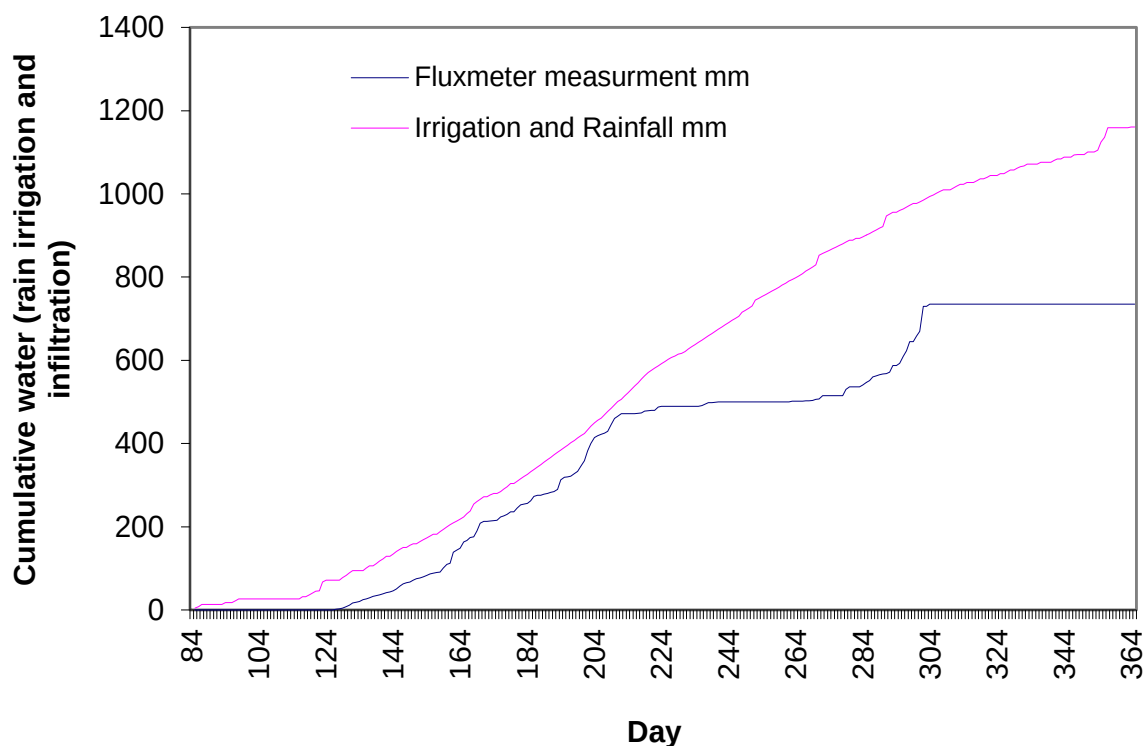


Figure 4. Cumulative drainage compared to sum precipitation (mm) and irrigation amount.

73.05‰ to -59.68‰ for δD . These results indicated that isotopic values of evaporating water vapor from soil surface (δ_E , soil evaporation) were more isotopically depleted relative to vapor generated by plant transpiration (δ_T)

during the tow sampling days. All samples (vapor, soil water, stem water, irrigation water) are situated around the local Meteoric Water Line (LMWL). The regression line of all samples intersect the LMWL at the point that presents

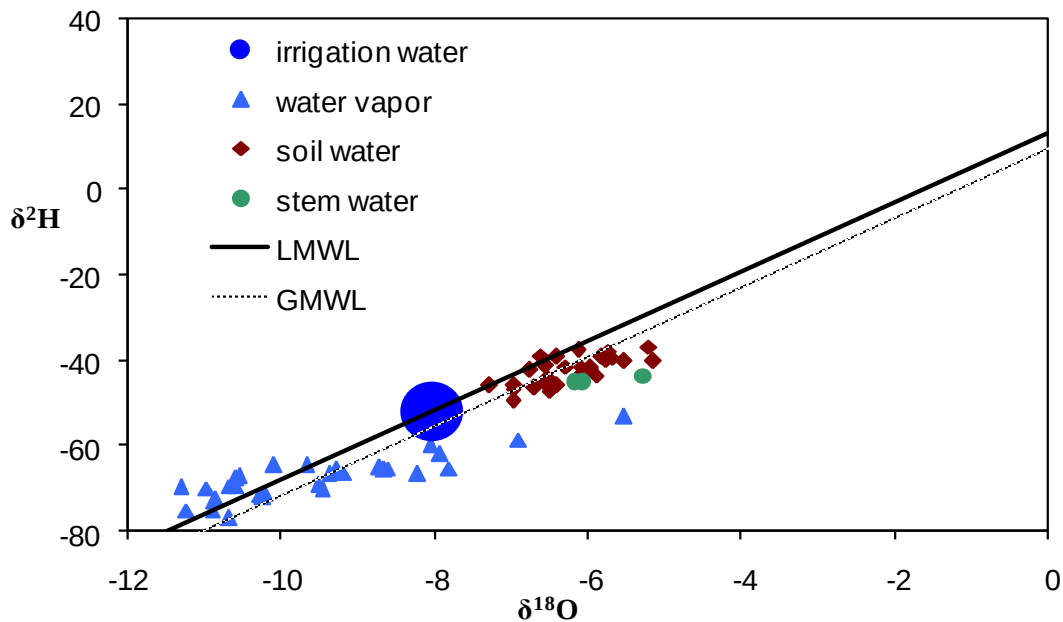


Figure 5: $\delta^{18}\text{O}$ versus δD in atmospheric water vapour, irrigation water, stem water and soil water in the Agafay site.

the origin of all samples (figure 5).

Keeling plot analysis

The isotopic ratio of the atmospheric water vapor at a certain altitude can be described using Equation (3) by considering mixing of evapotranspired water vapor and free atmospheric water vapor (Keeling, 1961; Moreira et al., 1997). This relationship is linear, and when used with water vapor the y-intercept reflects the source isotopic composition of the evapotranspiration flux:

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

Where δ_{ebi} is the isotopic composition of vapor collected from the ecosystem boundary layer, C_a is the atmospheric vapor concentration, C_{ebi} is 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 (Craig and Gordon, 1965) Equation 4:

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

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

In this paper $\alpha^* = 1/\alpha +$ (Gat, 1996) and $\alpha +$ can be calculated by the equation provided by Majoube (1971) Equation 5

$$^{18}\text{O}\alpha + = [1.137(10^6/T^2) - 0.4156(10^3/T) - 2.0667]/1000 + 1 \quad \text{Eqn5}$$

$$\text{D}\alpha + = [24.844(10^6/T^2) - 76.248(10^3/T) - 52.612]/1000 + 1 \quad \text{Eqn5}$$

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 $\text{H}_2\text{O}:\text{HDO}$ and 1.0281 for $\text{H}_2\text{O}:\text{H}_2^{18}\text{O}$ (Merlivat 1978).

The contribution of transpiration to evapotranspiration is estimated by Yakir and da Sternberg, (2000):

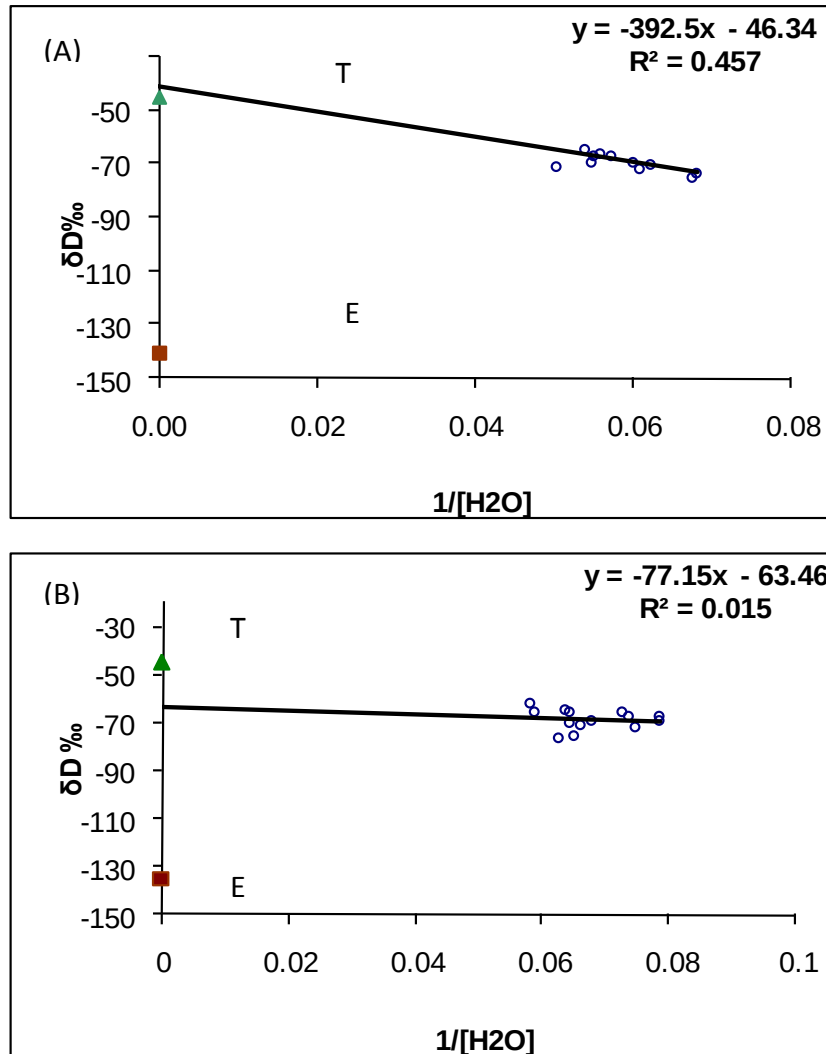


Figure 6. Relationship between δD at different levels above the ground and the inverse of the air absolute humidity in Agafay site (A 16/07/2009, B 17/07/2009) (E : evaporation, T transpiration)

$$F_T = \frac{\delta_{ET} - \delta_E}{\delta_T - \delta_E}$$

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

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

Considering orange crop transpiration as one source and

soil evaporation as another one, the fractional contribution of plant transpiration to total ET (T/ET) vary between 98 to 79.5% for δD during two day of sampling. Therefore transpiration dominates evaporation. This result confirms that the irrigation method applied by the farmer was very appropriate for the orchard conditions considering the evaporation as the only source of loss of water. The difference between the first and second day can be explained by the difference of environmental conditions. The average values of ET during the days of sampling are 3.18 and 3.85 mm for 16/07/2009 and 17/07/2009 respectively.

Williams et al (2004) combined Eddy covariance, sap flow, and stable isotope techniques to investigate the responses of transpiration and soil evaporation to an irrigation event in an olive orchard in Marrakech, Morocco, and the results show that transpiration accounted for

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	δET	R^2	P	n	δE	FT
16/07/2009	-41.4	-65.08	-44.63	-46.30	0.457	0.022*	11	-140.50	0.982
17/07/2009	-46.14	-68.53	-45.15	-63.464	0.015	0.67	14	-134.861	0.795

*The significance level is 0.05.

100% of total ET prior to irrigation, but only 69 –36% of ET during peak midday fluxes over the 5-day period following irrigation.

Conclusion

The stable isotopes content and Keeling plots allowed the partition of ET into different flux components for citrus orchard irrigated with drip irrigation. The experience made on two sampling days during July 2009 indicates that more than 80% of ET is mostly generated by plant transpiration.

However the loss by drainage is more important about 37% loss of sum cumulative irrigation and rainfall. This percolation which depends on irrigation was accentuates by precipitation.

These results confirm the efficiency of the irrigation system applied in Agafay station by considering just the evaporation loss. However the results showed also that a big amount of water was lost by percolation, infiltration and runoff. For that the farmer should re-examine amount of water applied and the timing of irrigation, in order to minimise the loss by percolation.

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