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Design and construction of a large weighing lysimeter in an almond orchard

I. J. Lorite[1]*, C. Santos[1], L. Testi[2] and E. Fereres[2, 3]

[1] *IFAPA-Alameda del Obispo. Consejería de Agricultura y Pesca, Junta de Andalucía. Avda. Menéndez Pidal s/n. 14004. Córdoba. Spain*
[2] *Instituto de Agricultura Sostenible-CSIC. Avda. Menéndez Pidal s/n. 14004. Córdoba. Spain*
[3] *Departamento de Agronomía, Universidad de Córdoba. Campus de Rabanales. Edificio C4 Celestino Mutis. Ctra. Madrid, Km. 396. 14071 Córdoba. Spain*

Abstract

Effective water management is essential to ensure the sustainability of irrigated agriculture. The accurate determination of crop water requirements is the first step in this task. This paper describes the building of a one-tree weighing lysimeter (3 × 3 m and 2.15 m depth) located in an almond (*Prunus dulcis* cv. Guara) orchard, inside the experimental farm "Alameda del Obispo" in Córdoba, Spain, to measure orchard evapotranspiration (ET_c). Following a review on lysimetry, the description of the construction of the weighing lysimeter is provided in detail, including considerations relative to system resolution and wind effects on the measurements. Finally, some preliminary results of the evaporation and transpiration of young almond trees are presented demonstrating that lysimetry in orchards provides accurate ET_c values needed to determine irrigation water requirements.

Additional key words: crop coefficients; evapotranspiration; irrigation; wind effects.

Resumen

Diseño y construcción de un lisímetro de pesada en una plantación de almendros

Un manejo del agua eficiente es esencial para asegurar la sostenibilidad de la agricultura de regadío. La primera tarea en este proceso es la determinación precisa de las necesidades hídricas de los cultivos. Este artículo describe la construcción de un lisímetro de pesada para la medida de la evapotranspiración (ET_c) del almendro (*Prunus dulcis* cv. Guara). El lisímetro está ubicado en la finca "Alameda del Obispo" en Córdoba, España, en el interior de una plantación de 5 ha, con unas dimensiones de 3 × 3 m y 2,15 m de profundidad y contiene un árbol. Partiendo de una revisión sobre lisimetría, se describe en detalle la construcción del lisímetro, incluyendo aspectos relacionados con la resolución y el efecto del viento sobre las medidas. Finalmente, se describen algunos resultados preliminares de evaporación y transpiración de almendros jóvenes, demostrando que la lisimetría para cultivos leñosos permite obtener valores precisos de ET, necesarios para la correcta determinación de las necesidades de agua de estos cultivos.

Palabras clave adicionales: coeficientes de cultivo; efectos del viento; evapotranspiración; riego.

Introduction

Given the competition for water resources, irrigation must be managed with the aim of improving the efficiency of water use. Precise knowledge of the crop water requirements (evapotranspiration; ET_c) is the starting point for improving agricultural water resources management. There are many methods to measure or estimate ET_c. Micro-meteorological techniques, such as the Bowen ratio and eddy covariance methods, are now commonly used for measurement of ET_c (Todd *et al.*, 2000; Payero *et al.*, 2003; Testi *et al.*, 2004). Even though measurements of ET_c from weighing lysimeters have been conducted since long ago

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*Corresponding author: ignacioj.lorite@juntadeandalucia.es
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Abbreviations used: CV (coefficient of variation); E (evaporation); ETc (evapotranspiration); ETo (reference evapotranspiration); Kc (crop coefficient); SD (standard deviation); T (transpiration); TDR (time-domain reflectometer).

(*e.g.,* van Bavel & Myers, 1962), they are still considered one of the most accurate methodologies to study the return of water to the atmosphere by the combined processes of evaporation and transpiration (Malone *et al.*, 2000), and are the standard method to directly measure ET_c (Reicosky *et al.*, 1983; Payero & Irmak, 2008).

Weighing lysimeters have a long history of development, and different designs have been used. Pruitt & Angus (1960) presented one of the initial reports on lysimetry. Some of the first lysimeters consisted of a big shallow tank (Pruitt & Angus, 1960), small rectangular containers (van Bavel & Myers, 1962), or small cylindrical tanks weighed with scales (England, 1963). Subsequent developments led to an increase in lysimeter size which then required the use of weighing mechanisms with advanced counterbalance weights (Ritchie & Burnett, 1968; Armijo *et al.*, 1972). Since that time, the majority of lysimeters incorporated balance beam and counterweight mechanisms (Malone *et al.*, 1999) that offset the dead weight from the soil and the container. A number of lysimeters using this methodology have been built (Wright, 1982; Marek *et al.*, 1988; Howell *et al.*, 1995, 1998) been the majority devoted to determining the ET_c of the major annual crops, such as alfalfa (Hunsaker *et al.*, 2002), wheat (Dugas *et al.*, 1985) or sorghum (Ritchie & Burnett, 1968).

More recently, improvements in design and cost of commercial load cells and data acquisition systems have enabled the design and installation of lysimeters which are completely supported by load cells without balance beam mechanisms or other moving parts (Allen & Fisher, 1990). The major drawback of the design as compared to mechanic designs is that the entire dead load (soil, container and crop) and live load of the tank are measured. Some lysimeters using load cells are described by McFarland *et al.* (1983), Schneider *et al.* (1998), Tyagi *et al.* (2000, 2003), Barani & Khanjani (2002), Girona *et al.* (2004), Jia *et al.* (2006), Loos *et al.* (2007), and Payero & Irmak (2008).

Agronomic applications of weighing lysimeters have been numerous. Among them, comparisons and analyses of different evapotranspiration estimation methods (Parlange & Katul, 1992; Kashyap & Panda, 2001), verification of the reliability of the ET_c estimates by means of the most recent updates of the FAO method (Lovelli *et al.*, 2005), measurement and comparison of ET_c in different cultivars (Ehlig & LeMert, 1976; Howell *et al.*, 1998), analyses and validation of models separating evaporation (E) and transpiration (T) (Klocke *et al.*, 1985; Qiu *et al.*, 1999), determination of basal crop coefficients and water requirements for specific Northwest US irrigated crops (Wright, 1982), alfalfa (Benli *et al.*, 2006) or garlic (Ayars, 2008), evaluation of methods to determine ET_o (López-Urrea *et al.*, 2006a,b), analysis of the relationship between evapotranspiration and soil water content (Brun *et al.*, 1985), deficit irrigation studies in peach trees (Girona *et al.*, 2002), analysis of the energy balance components (Aase & Siddoway, 1982), integration of Time-Domain Reflectometer (TDR) measurements and lysimetry (Young *et al.*, 1997), and finally, correlation between canopy light interception and crop coefficients (K_c) in apple and pear trees (Girona *et al.*, 2011).

In Spain, almond is an important tree crop, considering its cultivated area of 578,000 ha, of which only 6.7% is irrigated (Anuario de Estadística Agroalimentaria, 2010). Until recently, almond was considered a marginal crop in southern Spain, with average yields of around 200 kg ha^{-1} (Arquero *et al.*, 2002), while under irrigated conditions yields over 2,000 kg ha^{-1} are possible (Arquero *et al.*, 2002). These modern plantations are still scarce, but have high levels of productivity and profitability. Research related to almond irrigation management has been primarily carried out in California and Spain (Goldhamer *et al.*, 2003, 2006; Romero *et al.*, 2004a,b; García *et al.*, 2004; Girona *et al.*, 2005). These analyses have been mainly focused on regulated deficit irrigation studies, but information about its water requirements is still very limited.

The objective of this study is to describe the construction and performance of a weighing lysimeter containing a single almond tree, which was constructed within a new experimental almond orchard facility located in Córdoba, Spain. In addition, some young almond orchard evapotranspiration measurements collected in the weighing lysimeter are reported.

Material and methods

Field characteristics

The field where the weighing lysimeter was built is located in the province of Cordoba, southern Spain (37°51.5' N, 4°48.1' W), at 91 m of elevation and close to the Guadalquivir River. The field is flat and is 5 ha in size. Most lysimeter facilities are located in fields that do not exceed this area (Allen & Fisher, 1990; Jia *et al.*, 2006; Payero & Irmak, 2008). In our field, the lysimeter is located approximately in the center of the plot. Howell *et al.* (1985) indicated that a fetch of at least 100 m would be desirable for temperature and vapour pressure profile stability, and other authors have insisted in this fact (Marek *et al.*, 1988; Barani & Khanjan, 2002). Following these recommendations the minimum fetch in the "Alameda del Obispo" facility is 180 m in the predominant wind direction of West-East.

The soil in the experimental field "Alameda del Obispo" is uniform in the two upper meters due to the alluvial origin, and is described in Table 1. Deeper in the profile, an increase in sand content of the soil was detected. The soil is very deep (over 4 m) and there is no sign of a water table above that depth.

After completion of the construction of the lysimeter, the plantation was established in late February 2009 with almond trees (*Prunus dulcis,* cv. Guara). This self-fertile cultivar has a late flowering period adapted to frost that usually occurs in the area around late February. Although no pollinators were interplanted, the external rows of the field (around 200 trees) were planted with different almond varieties (Belona, Soleta, Vairo, Constantí, Marinada, Tarraco, Ferragnes, Ferraduel, Masbovera, Glorieta, Antoñeta and Marta).

Trees were planted at 7 m × 6 m spacing, for a total of around 1,300 trees in the field. A drip irrigation system was installed with a single drip line per row and emitters spaced 1 m with a discharge of 2.4 L h^{-1}. Every tree is thus irrigated with six emitters, including the one in the lysimeter. During summer 2009 measurements to determine the volume of the canopy and the fraction canopy cover for the tree located in the lysimeter were carried out using digital images software processing. The canopy volume in mid July was around 0.6 m^3 and the fraction cover around 4% (horizontal projection of the canopy was 0.34 m^2).

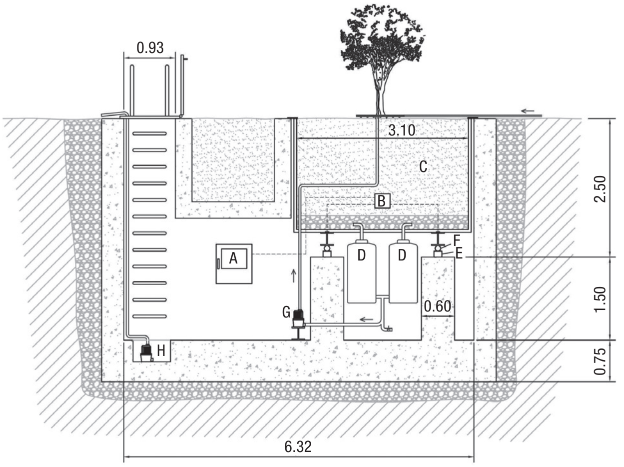
An automatic weather station (Campbell Scientific Inc., Logan, UT, USA) was used to collect standard meteorological data (wind speed and direction, solar radiation, relative humidity and temperature) at 10 min intervals over a 1.5 ha grass plot located 600 m away from the lysimeter. The grass plot was irrigated to meet full water demand (two irrigation events per week) and weekly mowed to obtain a homogeneous grass height of 0.12 m, following the recommendations of Allen *et al.* (1998) to satisfy the Penman-Monteith assumptions. The reference evapotranspiration (ET$_o$) was calculated using the Penman-Monteith equation (Penman, 1948; Monteith, 1965, 1973), applied on an hourly basis, using the normalised procedure of FAO (Allen *et al.*, 1998), assuming a standard grass surface resistance of 69 s m^{-1} during the day and 500 s m^{-1} during the night, and calculating aerodynamic resistance as 208/u (s m^{-1}), where u is the wind speed at 2 m height (m s^{-1}).

Construction process

Lysimeter construction started on February 2008 with the excavation. Due to the special requirements of size,

Table 1. Soil properties (density and texture) in the experimental field "Alameda del Obispo" close to the lysimeter

Depth (cm)	Density (g cm^{-3})	Depth (cm)	Sand (%)	Silt (%)	Clay (%)
15	1.63	30	30.4	52.6	17.0
45	1.50	60	27.0	50.7	22.3
75	1.54	90	30.0	50.4	19.6
105	1.44	120	31.9	45.1	23.0
135	1.54	150	37.6	44.4	18.0
165	1.60	180	46.8	39.3	13.9
195	1.59	210	57.2	32.1	10.7
225	1.57	240	50.6	35.0	14.4
255	1.55	270	47.4	38.8	13.8
285	1.55	300	53.1	33.9	13.0
325	1.53	330	76.4	17.5	6.1
375	1.56	360	43.5	37.4	19.1
		390	58.2	29.6	12.2
		420	34.0	51.6	14.4
		450	58.2	31.4	10.4



Lysimeter section

Figure 1. Sketch of the lysimeter showing the weighing system, control room, drainage system and access to the control room. A: transducer device, screen and datalogger. B: pressurized-gas high-voltage circuit breaker. C: stainless steel container. D: drainage deposits. E: load cells. F: steel ball supports. G: pump for irrigation from deposits. H: pump for control room drainage.

the total dug volume was around 100 m^3 (Fig. 1 and Suppl. Fig. 1, pdf). The duration of the construction was approximately 1 year, and 3 months more were required for the installation and calibration of the electronic devices (load cells, dataloggers and pumping system).

When the soil is highly structured with distinct profile characteristics, having an undisturbed soil monolith is essential for project objectives (Armijo *et al.*, 1972; Marek *et al.*, 1988; Schneider *et al.*, 1996). However, due to the homogeneity of the upper layers of the soil profile (Table 1), it was deemed not necessary to keep the soil undisturbed in the construction process.

Others authors proposed to remove the soil in small increments and then to refill the container maintaining the same characteristics as the surrounding soil (Ritchie & Burnett, 1968; Phene *et al.*, 1991; Ayars *et al.*, 2003; Johnson *et al.*, 2005). However, in relation with soil representativeness, Khan *et al.* (1993) indicated that if roots are well developed and nutrients and water supply are unrestricted, dissimilar soil may not cause significant variation in water use and yield.

In our case, the soil was separated into two layers (surface layer of 20 cm and the rest). To achieve a bulk density similar to that of the original soil (around 1.55 g cm^{-3}; Table 1), in the backfilling process, the soil was saturated with water every 30-40 cm depth increments, following a procedure described by Ritchie & Burnett (1968).

The buried control room contains the infrastructure for the load cell installation and instruments for pumping, data storage, etc. It was built with reinforced concrete with dimensions 4.3 m × 3.9 m with a depth of 4 m (Fig. 1 and Suppl. Fig. 1, pdf).

Weighing lysimeter characteristics

The weighing lysimeter consists of a stainless steel container with dimensions of 3 m × 3 m, and 2.15 m depth (Fig. 1). Few lysimeters exceed a soil profile depth of 1.5 m; only those described by Dugas *et al.* (1985), Phene *et al.* (1991), Howell *et al.* (1995), Schneider *et al.* (1996), Malone *et al.* (1999), Liu *et al.* (2002), Payero & Irmak (2008), and Evett *et al.* (2009) have a depth greater than 2 m, even though root water extraction could exceed 2 m depth (Allen *et al.*, 1998).

A drainage system is essential to avoid waterlogging in the container and it was installed before the soil refill process. Lysimeter drainage systems include vacuum-assisted systems (Phene *et al.*, 1989), porous bricks (Bhardwaj & Sastry, 1979) or suction candles built with porous ceramic tubes (Kirkham *et al.*, 1984). In our case, a 20 cm bed with pebbles with diameters around 1-2 cm (Suppl. Fig. 2b, pdf) and a pipe system of 2 cm of diameter inserted in the pebble bed were installed (Suppl. Fig. 2c, pdf). In order to avoid soil contamination of the pebbles-pipes system, a geotextile layer was placed between the soil and the drainage system (Suppl. Fig. 2a, pdf). The pipe system collects the drainage water that is stored in two plastic containers (Suppl. Fig. 3f, pdf) attached to the steel container and accessible from the control room. These containers have a capacity of 200 L each and are connected by a pipe to the lysimeter irrigation system (Suppl. Fig. 3e, pdf). A complete description of the drainage system and the access to the control room is shown in Figure 1.

The gap between the concrete wall and the stainless container is less than 1 cm to avoid alteration of the energy balance of the system (Barani & Khanjani, 2002). This gap has been covered in the surface with a flexible and impermeable PVC film (Suppl. Fig. 4, pdf). The container is supported and its weight measured by four load cells (Suppl. Fig. 3b, pdf). The installed load cells (HBM RTN) have an accuracy class C3 (according to OIML R60), with a nominal load of 10 t each and a very limited temperature effects and hysteresis and non-linearity errors. The four load cells are connected in series and installed with radial symmetry around the centre of gravity. This setup allows to reduce the wind effects on the measurement because the unload of one load cell (caused by the wind) is compensated by the overload of the load cell located in the opposite place.

The electrical signal from the four load cells is transmitted to a transducer device (model GI-308, Baxtran-Giropés, Girona, Spain) located in the control room (Fig. 1). This device, in addition to displaying the weight in a screen, transforms the signal from voltage (mV) to a digital signal that is collected by a datalogger (Model CR1000, Campbell Scientific Inc., Logan, UT, USA) through a RS-232 connection. The data collection protocol includes averaged weights, standard deviation (SD), signal and stability of the measurement. The maximum resolution of this device is 0.5 kg within a limited weight range (± 800 kg), so the system must be tared to have a weight around 800 kg at field capacity at the beginning of the irrigation season. The frequency of data collection was one measurement per second; averages were then calculated for each 5-min interval and stored in the datalogger memory. SD for the 300 instantaneous measurements was also calculated. This measurement frequency helped reducing adverse wind effects and is very high compared with previous studies of one measurement per minute (Payero & Irmak, 2008) or per 5 s (Dugas *et al.*, 1985). Finally, in order to analyse possible temperature effects on load cells resolution, the temperature of the control room is also measured and stored.

Following the data provided by the manufacturers of the load cells and the transducer device, and considering the container surface area (9 m^2), the resolution of the lysimeter installed is equal to 0.056 mm. This value can be considered acceptable following the indications of other authors (Marek *et al.*, 1988). In previous works, lysimeter resolution ranged between 0.01 mm for small lysimeters installed in the US Water Conservation Laboratory in Texas (van Bavel & Myers, 1962; Hunsaker *et al.*, 2002) and 1 mm for a lysimeter in a peach orchard (McFarland *et al.*, 1983). Since the relative error decreases with the magnitude of the ET_c measured, the resolution obtained here is adequate for measuring daily ET_c and longer periods, and even could be appropriate for shorter time steps. In order to ensure the precision of the measurement in the described lysimeter, six-monthly calibration checks by technical staff are carried out.

Measurement of crop evapotranspiration in conventional lysimeters is difficult when frequent irrigations events are required because the water added from an external source increases the mass of the lysimeter simultaneously with the decrease occurring from the evapotranspiration process. To avoid this, the lysimeter was equipped with a system that integrates its water supply which comes from containers attached under the lysimeter itself (Suppl. Fig. 3f, pdf). These water reservoirs are weighed with the lysimeter and refilled every day (preferably when ET_c is near minimum). Similar devices, described previously by Phene *et al.* (1989), Girona *et al.* (2002, 2004) and Ayars *et al.* (2003) allow the automatic measurement of ET_c without interruption (Phene *et al.*, 1989). This approach is especially useful in orchard trees with drip irrigation that require frequent irrigation events. However, in order to avoid a possible increase of salinity in the long term, the tree located in the lysimeter can also be irrigated with the field irrigation system.

The weighing lysimeter required a buried control room to contain the load cells, support of load cells, drainage containers, pumping system for irrigation, datalogger and electric devices. Equally a pumping system (independent of the lysimeter) was installed in the control room in order to extract possible water filtrations.

Features and issues regarding performance

Load cells installation

The load cells used in this lysimeter are extremely accurate but require a very careful installation under the stainless steel container. Initially six load cells were planned and installed but it was necessary to reduce its number to four due to elongation problems in the contact between the container and the load cells. This reduction in the number of load cells did not reduce the accuracy, although limited the maximum weight (from 60 to 40 t). In addition, four load cells increased the stability of the system, reducing the wind effects on the measurements.

The weight of the whole system (~ 35 t) caused significant deformations in the union between the container and the load cells, producing significant measurements errors as the weight values increased indefinitely without any physical reason. To avoid this problem, the base of the container was reinforced with an IPE steel beam support that avoid any deformation (Suppl. Fig. 3d, pdf), and a steel ball was inserted in the contact of the load cell with the support of the container (Suppl. Fig. 3c, pdf). On this support, the container was installed without any other type of union, allowing the free movement of the system.

Electrical damages

Electrical devices installed under field conditions could be damaged by lightning. In this case electronic load cells and electricity devices such as dataloggers may be in danger and require the installation of lightning protection systems. For this purpose a pressurized-gas high-voltage circuit breaker was installed upstream the load cells transducer; additionally, the stainless steel container was grounded by welded copper cables (Suppl. Fig. 3a, pdf).

In addition, the power supply was equipped with traditional protections against voltage anomalies (differential circuit breaker), and the datalogger and load cells were equipped with an uninterrupted power supply system (UPS device).

Wind speed

The main wind effect on the lysimeter measurements is momentum flux, causing important measurement fluctuations. In our installation, measurements were collected every second and averaged every 5 minutes to mitigate this perturbation.

Wind greatly affects the scale performance and accuracy (Ritchie & Burnett, 1968; Howell *et al.*, 1995; Malone *et al.*, 1999; Vaughan & Ayars, 2009). For crops as sorghum 15-min SD was consistent at about 0.42 mm for winds less than 5 m s^{-1}, but increased with wind speeds about 5 m s^{-1} (Howell *et al.*, 1995). Similar conclusions were reached for a weighing lysimeter with Festuca by Martínez-Cob & Baselga (1999) which obtained SD of 0.13 mm with 30-min periods for wind speed lower than 3.5 m s^{-1}, but was as high as 0.80 mm for wind speeds above 6 m s^{-1}. In order to avoid these vibration problems, some authors used filtering computer programs to reduce the SD (Vaughan *et al.*, 2007; Vaughan & Ayars, 2009), or electronic filters to reduce the amplitude of oscillations (Ritchie & Burnett, 1968), although repeated readings has been the most used procedure to minimize the wind effects (van Bavel & Myers, 1962; Tyagi *et al.*, 2003; López-Urrea *et al.*, 2006b). Thus, in order to avoid the perturbation in the measurements produced by the wind, López-Urrea *et al.* (2006b) suggested to increase the frequency of measurement, averaging them in time intervals between 10 and 30 min, and Dugas *et al.* (1985) proposed to average 5-s sample values for a 10-min period obtaining measurements independent of wind.

Measurement resolution

The main limitation of lysimeters without counterbalance mechanisms to achieve good resolution is the accuracy of the load cell. However, with the use of new devices that weigh directly the whole system (container, soil and tree), an additional limitation results from the resolution of the datalogger (Payero & Irmak, 2008). Thus, the resolution and precision of evapotranspiration measurements could be limited more by the datalogger and multiplexer combination than by the load cells (Allen & Fisher, 1990). In our case, following the manufacturer specifications and considering the load cell and datalogger characteristics, the measurement resolution was equal to 0.056 mm (0.5 kg), as described above. However, if the voltage signal provided by the load cells was directly used without any amplification of the signal, the maximum resolution would be around 1.5 kg and 0.17 mm.

Efforts to increase the resolution with current technology could only be obtained by changing from a load cell system to a counterbalance system, because load cells with better sensibility are not yet available. However, the manufacturer advised against this option considering maintenance reasons. In any case, wind effects could disguise this improvement, as shown long ago by van Bavel & Myers (1962), especially in the case of a tree. These authors indicated that due to wind effects, there is little practical improvement in accuracy with lysimeters that are more sensitive than 0.01-0.05 mm.

A range of resolution between 0.02 mm and 0.05 mm is required to obtain hourly ET_c rates (Dugas *et al.*, 1985; Howell *et al.*, 1985; Schneider *et al.*, 1998; Girona *et al.*, 2004; López-Urrea *et al.*, 2006a). Malone *et al.* (2000) proposed a maximum relative error of 10% for hourly ET_c estimations, implying that for the lysimeter reported here a threshold ET_c of 0.56 mm $hour^{-1}$ is required to obtain reliable hourly values.

Temperature effect on sensitivity according to the manufacturer is very small (± 0.008% of sensibility for each 10 K). However if the range of variation in temperature is very high there could be significant errors (Allen & Fisher, 1990). In our case, these errors are minimized because the load cells are installed in the control room below ground, where temperature fluctuations are attenuated. Kirkham *et al.* (1984) detected temperature changes of less than ± 0.2°C day^{-1} in the buried scales located at 2 m depth in two weighing lysimeters built in Washington State (USA), and were similar to the values measured in our lysimeter.

Effect of condensation on the measurements

Condensation was detected during the nights on the soil contained in the lysimeter and on the internal walls of the container. Thus, an increase in weight after sunset was measured in numerous days. The environmental conditions in the control room are characterized by high humidity and a stable, moderate temperature. These conditions may affect the measurements due to the occurrence of condensation on the walls and base of the steel container during the evenings, when temperature of the container decreases. Although the amount of condensed water is low (~ 1 kg day^{-1}), it may represent a significant error in days of very low ET$_c$. To avoid this effect, a dehumidifier capable of removing 20 L of water each 24 h was installed in the control room. For daily measurements during summer time, ET$_c$ and T computations were carried out as the difference in weight from 19:00 GMT of the day before and the current, while for winter time the computed time was considered from 16:00 GMT. The measurement time (19:00 and 16:00 GMT) was chosen to obtain data previous to the beginning of the condensation process, considering that at that moment the lysimeter conditions are similar during successive days.

Results

Wind speed effects on ET$_c$ measurements

Wind speed effects on the measurements were analysed by calculating the SD of the total weight for 10-min periods, a period that matched the measurement output rate of the weather station. The SD of the measurements during summer 2009 had an average value of 0.36 kg (0.04 mm), with an average wind speed of 2.12 m s^{-1}. The lowest SD values (around 0.32 kg) were observed during the night with an average wind speed of 1.3 m s^{-1}, although in the periods with absence of wind no changes in the ET$_c$ measurement were detected (CV = 0). Considering the summer daytime only (from 6:00 GMT to 19:00 GMT), the SD increased to 0.39 kg, caused by a faster wind speed (2.68 m s^{-1}), and the measurement changes due to the simultaneous evapotranspiration losses. To quantify the effects of ET$_c$ variations on measurement variability, we calculated the SD of the measurement after removing wind speed effects. During daytime in the summer, this SD was equal to 0.01 kg, implying that during daytime more than 97% of the observed variability was caused by wind speed.

A correlation between wind speed and variability in the measurement was detected (Fig. 2). For the whole day, a weak correlation (R^2 = 0.37) was found. However, if only the night time data were analysed, this correlation increased to R^2 = 0.7 (Fig. 2).

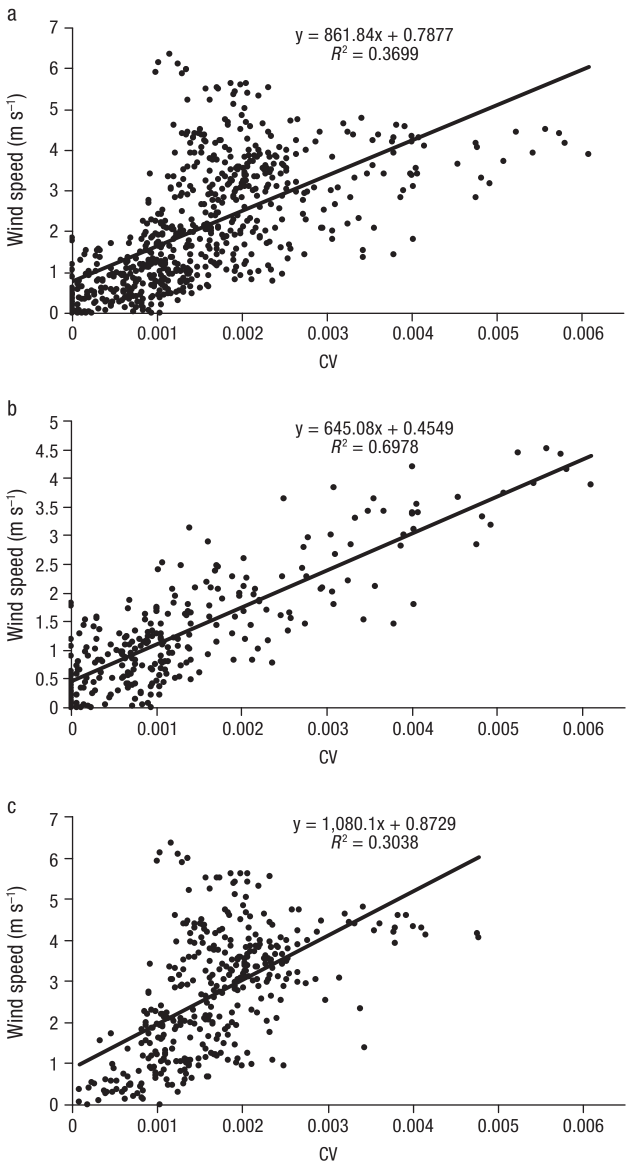


Figure 2. Correlation between wind speed and coefficient of variation of the measurement in 5-min periods for the whole data set (a), night-time (b) and daytime (c).

Evapotranspiration of a young almond tree

Evapotranspiration (the sum of tree T and E from soil) was measured every 5-min period with high accuracy. Figure 3 presents the evolution of cumulative ET_c for 12 days in June, 2009. The 5-min records setup allow to reduce losses of data for long periods (30-min or 1-hour periods) when lysimeter maintenance is carried out (pruning, weed control, etc.).

The periods of irrigation (fall in ET_c due to the increase of weight) and periods of drying are clearly detected. Due to the small tree canopy (see Material and Methods section), ET_c depended on the time since last irrigation event in the sense that ET_c is mainly evaporation from soil. Thus, for example in the second week of June, daily ET_c one day after the irrigation event was equal to 1.6 mm day^{-1} (14.5 L day^{-1}), while two days later, ET_c was reduced down to 1.3 mm day^{-1} (11.6 L day^{-1}). The ET_c values reported here reflect directly the weight loss of the lysimeter and need to be corrected to reflect the fact that tree spacing (6 m × 7 m) is greater than the surface area occupied by the lysimeter (3 m × 3 m).

In order to eliminate the evaporation from the bare soil, the soil of the lysimeter was covered with transparent plastic and fixed to the borders to avoid loss of water from the soil surface, procedure described by Ayars *et al.* (2003). To keep the soil surface conditions similar to the rest of the field, the plastic was covered with a soil layer of around 2 cm, obtained from the surrounding area of the lysimeter.

Figure 4 presents lysimeter measurements of T for three measurement frequencies, compared against the ET_o daily pattern. Using 5-min averaged data showed some disruptions due to variations in wind speed affecting the cumulative T during some measurements (Fig. 4a). This was corrected when the data was averaged in 30-min periods, with only two periods having questionable values. With hourly data the curve was very stable (Fig. 4c). For the three scales, the T curve behaved similarly to the ET_o curve, suggesting that the T determination with the lysimeter was valid. Declines in the T curve were caused by condensation processes previously described.

The transpiration coefficient ($K_T = T/ET_o$, non-dimensional) values for the almond orchard during the analysed period (7-11 July 2009) was equal to 0.02. Daily average transpiration value for the same period was 6 L tree^{-1} (Fig. 5). Similar to previous analyses, a clear correlation between transpiration and ET_o was

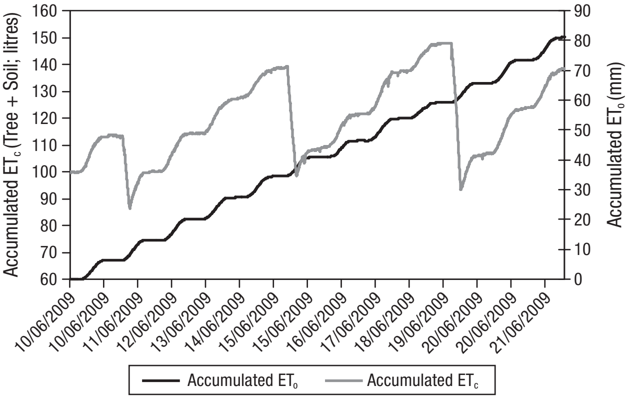


Figure 3. Accumulated ET_c and ET_o averaged in 5-min periods for the period between 9th and 22nd of June 2009, including irrigation and drying periods.

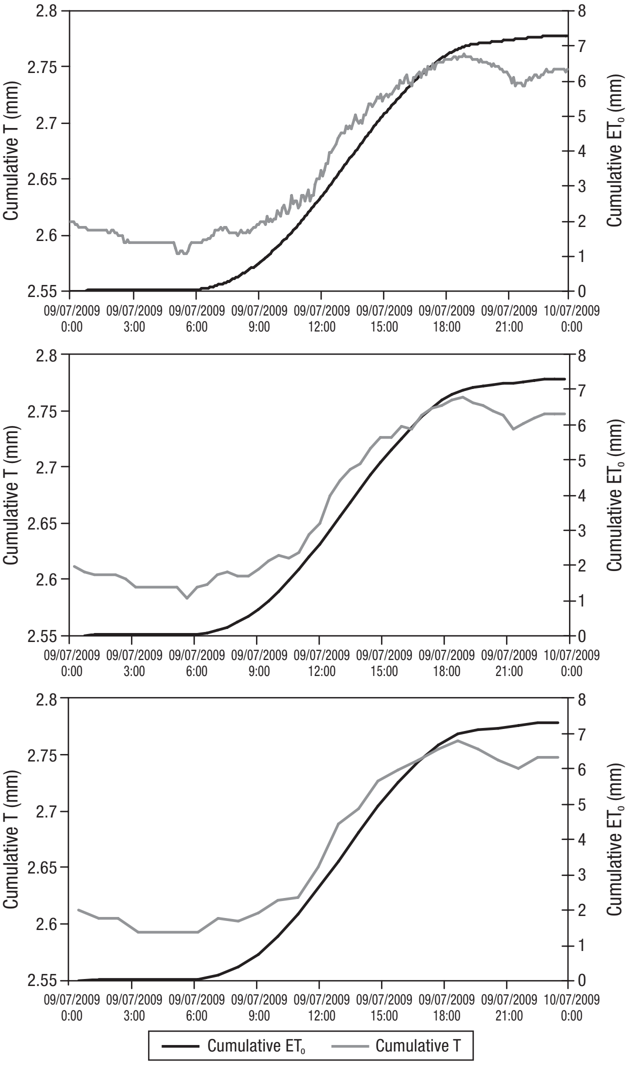


Figure 4. Cumulative transpiration (mm) for 9 July with three different averaging periods: a) 5-min, b) 30-min and c) 1-hour. Cumulative ET_o is also shown.

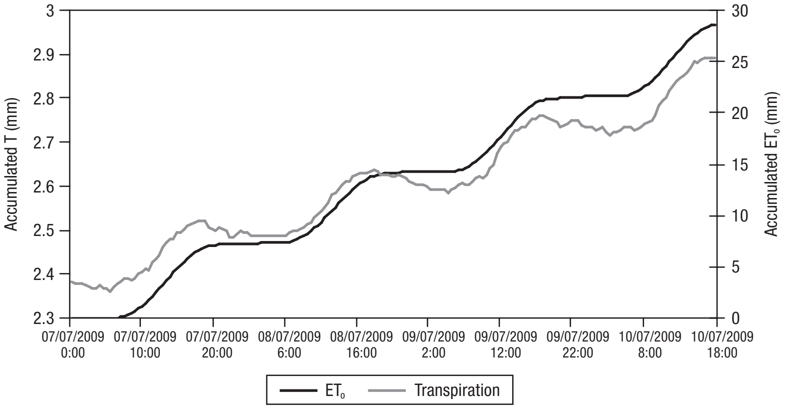


Figure 5. Accumulated transpiration averaged in 30-min periods and accumulated ETo for the period between 7th and 11th July 2009.

detected. An example of condensation effects on the measurements are shown in Figure 5 with data collected after 20:00 GMT in the evening. A detectable increase in weight (~ 1 kg) was measured close to sunset as the container is cooling (causing condensation), with a similar weight reduction some hours later.

Analysing hourly results, the period between 12:00 GMT and 13:00 GMT was the period with higher rate of transpiration (for 9th of July this value was equal to 1.6 L h^{-1} $tree^{-1}$; Fig. 6). Lower values were detected for the rest of the day, with a similar curve than for the solar radiation and ET_o. T rates in the early morning (around 7:00 GMT) could be caused by the evaporation of the condensation water accumulated during the night on the bare soil of the lysimeter. As stated above, accurate hourly T values may be obtained under high ET_o rates.

Evaporation from bare soil is important to establish a water balance (Loos *et al.*, 2007). Here, E from soil was measured during autumn/winter at a time when there was no transpiration from the almond tree. Figure 7 shows the evaporation rates for the period after an abundant rainfall (34 mm on 20-22 October period). Daily evaporation values ranged from 0.6 to 1.9 mm, with K_c values declining from 0.65 to 0.38 in a 13-day period after rainfall. In spite of the low absolute E values, the lysimeter was able to detect the small variations in evaporation and K_c.

Discussion

Lysimetry for determining the ET_c of orchards is a viable method, although it has a number of complexities as compared to simpler estimation methods. For instance, the construction of a precise weighing lysimeter is complex and requires careful consideration of numerous aspects if an accurate and efficient instrument for ET_c determination is sought. The location, construction procedures, weighing mechanisms and effects of external factors such as the wind speed, must be studied in advance, specially with tree crops where some adverse effects are enhanced, to avoid malfunctioning

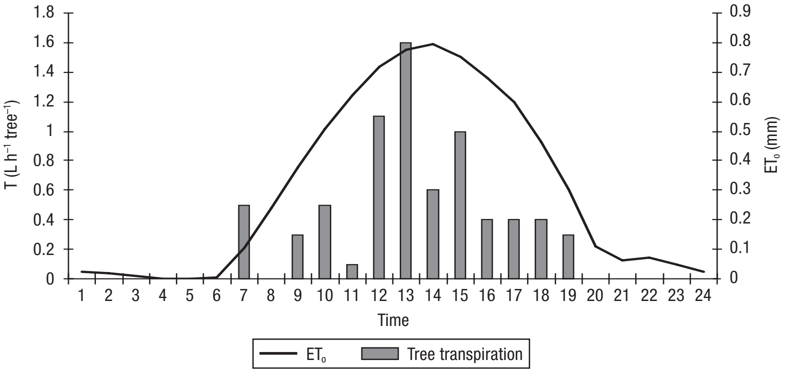


Figure 6. Hourly transpiration rate (litres per hour and tree) and ET_o for a representative day during summer 2009 (9th July).

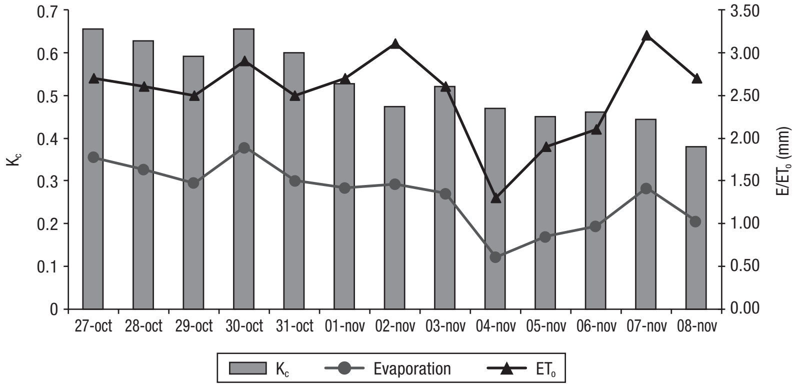


Figure 7. Daily ET_c values measured with the weighing lysimeter, ET_o and K_c values for the period from 27 October to 8 November 2009.

that would, lead to inaccuracies, data gaps and important over costs. Due to these concerns, the majority of weighing lysimeters have been used to grow annual crops (Wright, 1982; Tyagi *et al.*, 2000, 2003; Liu *et al.*, 2002; Lovelli *et al.*, 2005; Miranda *et al.*, 2006; López-Urrea *et al.*, 2009a,b), while growing trees or vines in them has been less common. Lysimeters with trees have been reported by McFarland *et al.* (1983), Girona *et al.* (2002, 2004), Yang *et al.* (2003), Ayars *et al.* (2003) and Johnson *et al.* (2005), among others, but to our knowledge, almond trees have not been planted in large, weighing lysimeters. One of the limitations of tree lysimeters, is the practical impossibility of having a surface area in the lysimeter identical to the tree spacing outside. This is required to exactly reproduce in the lysimeter the evaporation from the soil surface outside the lysimeter. In this case (6 m × 7 m), it would have meant building a lysimeter that would be about five times heavier, with the equivalent loss in precision. Thus, the E component of ET_c must be estimated by other means.

The resolution obtained with the weighing lysimeter (0.056 mm) provided sufficient accuracy to measure precisely daily ET_c values, and under high evapotranspiration demand, accurate hourly ET_c values may be determined. Thus, compared with others lysimeters with similar technology (load cells without balances and/or counterweights), the described lysimeter provided very accurate resolution relative to other lysimeters (resolution ranged from 0.053 mm for pears and apples described by Girona *et al.* (2004) to 1 mm in peach described by McFarland *et al.* (1983)). Equally, compared with lysimeters with balances and counterweights, the resolution was also remarkable (resolution of these lysimeters ranged from 0.01 mm obtained by van Bavel & Myers (1962) and Hunsaker *et al.* (2002), to 0.064 mm obtained by Evett *et al.* (2009)).

The methodology for collecting data (averaged 5-min with a frequency of one second) plus the new load cell technology and installation reduced significantly the wind effects on the quality of the measurement, obtaining very satisfactory results in reducing the variability in the measurement (0.36 kg). These results were even more accurate than previous studies carried out on lysimeters with short-crops (Howell *et al.*, 1995; Martínez-Cob & Baselga, 1999).

The infrastructure described here due to its specific characteristics could constitute the base of numerous studies related with water use, remote sensing and crop modelling for orchards. Thus, thanks to the field size and the accurate resolution obtained in the lysimeter, validation of remote sensing techniques (such as energy balance models) could be carried out. Equally, the development of water balance models quantifying separately E and T will contribute to an accurate determination of irrigation water requirements for orchards.

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