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DETERMINACIÓN DE LAS NECESIDADES HÍDRICAS DEL OLIVO MEDIANTE LISIMETRÍA

por

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RESUMEN

En la década del 2000 hubo una rápida expansión de la producción de olivos en Uruguay. La mayoría de los estudios existentes sobre la evapotranspiración del cultivo (ET_c) en olivo fueron desarrollados en climas áridos y semiáridos. La aplicabilidad de esos resultados en las condiciones climáticas de Uruguay aún necesita ser probada. Durante dos estaciones de crecimiento se midió la ET_c de olivos jóvenes en etapa no productiva, trasplantados en lisímetros de drenaje protegidos de la lluvia por una estructura con cierre automático. El volumen de agua de riego y drenaje de cada lisímetro se midió diariamente y la humedad del suelo se registró dos veces por semana con sonda de neutrones. La ET_c se calculó por balance de volúmenes de agua. Con la finalidad de mejorar la estimación de evapotranspiración (ET_c) y su uso para una amplia gama de condiciones de producción, se eliminó el componente de evaporación directa del suelo de la evapotranspiración medida total, determinando el coeficiente de cultivo basal (K_{cb}). Se realizaron medidas con micro-lisímetros para cuantificar la evaporación del suelo (E_s) y se restó de la evapotranspiración (ET_c) para determinar la transpiración. El coeficiente basal medio mensual (K_{cb}) se determinó como (ET_c-E_s) / ET_o, donde ET_o es la evapotranspiración de referencia calculada a partir de datos meteorológicos locales. La evolución de K_{cb} se modeló para una estación de crecimiento desde el inicio del crecimiento vegetativo (DPGI 1 = 11 de julio) y se buscó desarrollar una herramienta predictiva para K_{cb} que se pueda utilizar en el manejo práctico del riego. Se exploraron dos opciones: 1) expresando K_{cb} en función de los días luego del inicio del crecimiento vegetativo (DPGI) y 2) relacionando K_{cb} con la intercepción de luz del mediodía. El patrón estacional de K_{cb} y sus valores por etapa de crecimiento fueron similares a los descritos en la literatura para los climas mediterráneos. Los valores máximos se registraron en otoño y los mínimos al comienzo de la primavera. La variación del K_{cb} se explicó satisfactoriamente mediante la medición de la intercepción de la luz del dosel (FIR).

Palabras claves: evapotranspiración, coeficientes del cultivo, contenido de agua en el suelo, necesidades de riego, *Olea europea* L.

SUMMARY

DETERMINATION OF THE WATER REQUIREMENTS IN OLIVE TREES WITH LYSIMETERS

In the 2000s there was a rapid expansion of olive production in Uruguay. Most studies on the crop evapotranspiration (ET_c), and irrigation of olive trees were developed in arid and semi-arid climates. The applicability of those research results under the climatic conditions of Uruguay still needs to be tested. Young non-bearing olive trees cv Arbequina were grown in drainage lysimeters and their water consumption was measured over two consecutive experimental periods protected from rain by an automatic rain-out shelter. Irrigation water volume and drainage of each lysimeter was measured daily and soil moisture was registered twice a week with neutron probe. Evapotranspiration (ET_c) was calculated by water volume balance. To improve the resulting ET_c estimates for a wide range of olive orchard production conditions, it was removed the soil evaporation component from the total measured crop evapotranspiration and it was determined the basal crop coefficient (K_{cb}) for the humid climatic conditions of Uruguay. Micro-lysimeter measurements were used to quantify soil evaporation (E_s) and E_s was subtracted from evapotranspiration (ET_c) to determine transpiration. Monthly mean (K_{cb}) were determined as $(ET_c\text{-}E_s)/ET_o$, where ET_o is reference evapotranspiration, calculated from locally measured weather data. The evolution of K_{cb} was modeled for a growing season from the start of vegetative growth (DPGI 1 = July 11).

In addition, the study seeks to develop a predictive tool for K_{cb} that can be used in practical irrigation management. Two modeling options were explored: 1) by expressing K_{cb} as a function of days past growth initiation (DPGI); and 2) by relating K_{cb} to the midday light interception. Seasonal patterns of K_{cb} are presented and the K_{cb} values by growth-stage were found to be similar to those described in the literature for Mediterranean climates. Variation of the basal crop coefficient was satisfactorily explained by measured canopy light interception (FIR).

Key words: evapotranspiration, crop coefficients, soil water content, irrigation requirements, *Olea europea* L.

1. INTRODUCCIÓN

1.1 SECTOR OLIVÍCOLA EN EL URUGUAY

El cultivo del olivo se ha desarrollado tradicionalmente en la cuenca del Mediterráneo, con España, Italia, Grecia como sus principales productores. Sin embargo en los últimos años, según datos del Consejo Oleícola Internacional (2018), se han incorporado al sector olivícola otros países como Argentina, Chile y Australia.

Asimismo a partir del año 2003 comenzó en el Uruguay un importante proceso de expansión en la producción de este cultivo, con un incremento anual sostenido, alcanzando en la actualidad las 9000 hectáreas según estimaciones de la Asociación Olivícola Uruguaya (ASOLUR, 2016).

El sector olivícola de Uruguay ha sido un importante captador de inversiones extranjeras, especialmente de Argentina y Europa, que lo han posicionado en el segundo rubro frutícola por superficie del país, tras los cítricos (Tommasino, 2012). Esta rápida evolución del sector se ha visto favorecida por la coincidencia de una serie de factores físicos y climáticos que son propicios para esta producción. El Uruguay está ubicado dentro de la latitud aceptada internacionalmente como apta para el desarrollo del cultivo, entre 30º y 45º (Civantos, 2008), si bien no todos los suelos cuentan con el buen drenaje requerido para esta producción, existen áreas con terrenos adecuados en diferentes zonas del país que son de baja productividad para la ganadería y la agricultura de cultivos anuales. Se agrega a lo anterior que tanto por cercanía como por acuerdos comerciales, Uruguay ofrece un acceso privilegiado a los grandes mercados importadores como Brasil, Estados Unidos y Canadá (Blasina y Asociados, en "El Observador" del 8 de agosto de 2013).

Las principales zonas de producción olivícola son los departamentos de Maldonado, Colonia, Rocha, Salto, Treinta y Tres y Lavalleja.

Los montes de olivo del país son intensivos, con marcos de plantación de 7 m x 5 m ó 6 m x 4 m (285-416 árboles ha^{-1}) y una media de 357 olivos por hectárea. Esta densidad de plantación busca una mayor productividad específica por unidad de superficie, durante un mayor número de años y permite realizar la cosecha en forma semi-mecanizada (Parras Rosas, 2012). La entrefila se mantiene con pasturas permanentes, para facilitar el tráfico de maquinaria pesada durante los períodos húmedos.

El material vegetal procede principalmente de viveros locales, donde se producen una treintena de variedades. La variedad Arbequina es la que predomina en superficie, ocupa (50 % del total), pero las variedades Frantoio, Barnea, Picual, Coratina y Leccino, también tienen una presencia importante (Parras Rosas, 2012).

La mayor parte de la producción se destina a la obtención de aceites de oliva, y solo una pequeña proporción se destina a la elaboración de aceitunas de mesa.

La producción del país está orientada a la obtención de aceites de oliva de buena calidad. Los aceites de oliva extra virgen uruguayos están siendo distinguidos con importantes premios en concursos internacionales y esto ha posicionado a Uruguay entre los diez países productores con mejor calidad de aceite de oliva virgen extra (ASOLUR, 2016). En este sentido se lanzó el sello de Calidad Premium el cual certifica, mediante auditorías realizadas por la Facultad de Química (Udelar), que los aceites con este distintivo cumplen con los valores preestablecidos de una serie de parámetros y carecen de defectos organolépticos.

Recientemente Uruguay fue aceptado dentro del Consejo Oleícola Internacional, organismo que nuclea a los principales países productores de aceite de oliva y aceitunas de mesa. La inserción del Uruguay en este organismo podría facilitar su posicionamiento en el comercio internacional.

Actualmente la producción oleícola del país trabaja dentro del marco de un conglomerado (Conglomerado Agroindustrial Olivícola de Uruguay), donde participa la Oficina de Planeamiento y Presupuesto (OPP), el Ministerio de Ganadería Agricultura y Pesca, Ministerio de Industria, la oficina de promoción Uruguay XXI y ASOLUR. En el Plan Estratégico elaborado por este conglomerado se hace referencia a que la gestión del agua en el olivar ha de ser una línea prioritaria de investigación, junto a los aspectos fitosanitarios.

1.2 RELACIONES HÍDRICAS DEL OLIVO

El olivo es una especie mediterránea, con una gran adaptación morfológica y fisiológica a condiciones de extrema sequía. Su sistema radicular es extenso y en terrenos arenosos puede alcanzar varios metros de profundidad y un desarrollo lateral que puede triplicar el diámetro de la copa (Rapoport, 2008). Sin embargo, Searles et al. (2009) reportaron para montes comerciales regados en una zona árida del Noroeste de Argentina, que las raíces absorbentes se concentraron en los 50 cm más superficiales de suelo y lateralmente en los 50 cm más cercanos a la línea de goteros.

Sus hojas son coriáceas y cuentan con pocos estomas que están ubicados solo en el envés (Connor, 2005). Los estomas están dispuestos en ligeras depresiones cubiertas parcialmente por pelos, donde se crea un microclima más húmedo que disminuye la transpiración (Rapoport, 2008) El olivo mantiene un balance favorable entre fotosíntesis y transpiración, debido a su patrón de apertura estomática. Dado que la máxima apertura estomática se da en las primeras horas de la mañana cuando el déficit de presión de vapor es mínimo, la entrada del CO_2 se produce con un gasto transpirativo menor que al mediodía. Aún en árboles de olivo bien hidratados ocurre ajuste estomático en respuesta al aumento del déficit de presión de vapor, con sus correspondientes disminuciones de asimilación de CO_2 (Orgaz y Fereres, 2008). Las hojas jóvenes de las brotaciones del año mostraron un mejor control estomático que las hojas del año anterior (Fernández et al., 1997).

La tasa fotosintética de la hoja es relativamente alta, del orden de 12 a 20 µmol CO_2 m^{-2} s^{-1}, pero se reduce cuando se produce ajuste estomático (Gucci y Fereres, 2012). La temperatura óptima para el proceso de fotosíntesis es alrededor de 28°C (Carr, 2013).

Según Moriana y Fereres (2002), observaron en árboles bien hidratados tasas de fotosíntesis y conductancia estomática altas durante el otoño y bajas en los días con alto déficit de presión de vapor. Asimismo Gucci y Fereres (2012), indicaron que la transpiración relativa de los olivos, directamente relacionada con la conductancia estomática, muestra una marcada variación anual, con valores mínimos en primavera y valores máximos a principios de otoño.

1.3 PRODUCCIÓN DEL OLIVO CON RIEGO

A pesar de su adaptación a los climas áridos, esta especie responde a las aportaciones de agua por medio del riego, traduciéndose en un rápido crecimiento de la planta joven promoviendo la entrada temprana en producción, así como en kilogramos de aceitunas producidas (Moriana et al. 2003, Fernández y Moreno 1999). Mediante el riego se pueden obtener rendimientos promedios de 10-15 t ha^{-1}, reduciendo la alternancia de producción entre años (Gucci y Fereres, 2012).

A mediados del siglo XX, en los países productores de oliva se comenzó a introducir el riego en montes que hasta ese momento venían produciendo en secano. Esta práctica condujo a un aumento en la producción tanto de la aceituna de mesa como del aceite. En forma paralela se iniciaron programas de mejora vegetal con el fin de desarrollar nuevas variedades con mayor respuesta productiva al nuevo régimen hídrico. Posteriormente la necesidad de mayor rentabilidad de la producción condujo al desarrollo de nuevos sistemas de plantación y cultivo, surgiendo las plantaciones de alta densidad, en setos, permitiendo la mecanización de la cosecha (Fernández-Escobar et al., 2012).

La aparición del riego por goteo facilitó el riego de los montes de olivo ubicados en topografías con pendiente alta y permitió compatibilizar el riego con la mecanización requerida en el resto de las prácticas de manejo del monte.

1.3.1 Respuesta al riego del olivo

En el caso de montes de olivo jóvenes, cualquier estrategia de riego deficitario supone una reducción en el crecimiento, demorando la entrada en plena producción (Orgaz y Fereres, 2008). Según Iniesta et al. (2009) tanto los árboles sometidos a riego reducido continuo (RDC) como los sometidos a un déficit de riego regulado

(RDR) redujeron fuertemente el crecimiento vegetativo en comparación a los árboles bien regados.

Un buen aporte hídrico tanto por las precipitaciones como por el riego, es beneficioso durante todo el ciclo anual, sin embargo los períodos críticos al déficit hídrico son la pre-floración, la floración y la maduración de los frutos (Orgaz y Fereres, 2008). Si bien la falta de agua en cualquier momento del año provoca reducción del crecimiento y del número de flores al año siguiente, cuando el déficit hídrico ocurre durante la pre-floración y la floración puede provocar el aborto de flores y una reducción en la fecundación respectivamente, por esta razón es fundamental la práctica del riego durante los inviernos y primaveras con bajas precipitaciones, sobre todo en suelos con baja capacidad de retención.

Dado que el crecimiento de la aceituna como el de cualquier otra drupa, se ajusta a una curva doble sigmoide. El crecimiento inicial del fruto (etapa I) y el periodo de acumulación del aceite en el fruto o lipogénesis (etapa III) son sensibles al déficit hídrico. Sin embargo, la segunda fase del crecimiento del fruto, desde el endurecimiento del carozo hasta el comienzo de la maduración, es reportada como la etapa más resistente al déficit hídrico pero no es recomendable que se suspenda totalmente el riego sino que se mantengan dosis mínimas (Iniesta et al. 2009, Moriana et al. 2003).

Entonces en zonas donde existe escasez de agua, la estrategia es utilizar una cantidad de agua menor que la necesaria para obtener una producción total y distribuirla en la máxima área posible procurando evitar el estrés hídrico cuando el cultivo es más sensible (p. ej., durante la floración o la lipogénesis). Esta estrategia se conoce como “riego deficitario regulado” o RDR.

En Uruguay, la plena floración del cultivar Arbequina se presenta alrededor de la última semana de octubre, la etapa del endurecimiento del carozo se da alrededor de la última semana de diciembre y primera semana de enero, mientras que la maduración del fruto se presenta a mediados de marzo y abril, según datos presentados en la Jornada de Divulgación (INIA, 2010). Por tanto en nuestras condiciones, sería imprescindible atender las necesidades hídricas del cultivo a partir de los últimos días de agosto hasta diciembre y luego a partir de marzo hasta la cosecha.

Según Alegre et al. (2002), riegos con dosis equivalentes al 50 % ET_c, desde el comienzo del endurecimiento del carozo hasta fin de setiembre (hemisferio norte), no disminuyeron el rendimiento en aceite pero sí disminuyeron la floración del año siguiente lo cual podría limitar el rendimiento futuro del monte.

Moriana et al. (2003) ajustaron una curva cuadrática que relaciona el rendimiento en kg de aceite por hectárea (R) con la ET_c, para un olivar adulto con un marco de plantación de 6 m x 6 m, en Córdoba, España.

$$R = -2780 + 11 * ETc - 0.006 * ETc^2$$

De esta función se desprende que tanto el rendimiento como la eficiencia en el uso del agua son crecientes hasta cierto valor y luego descienden a medida que aumentan las cantidades de riego (valores altos de ET_c). La máxima eficiencia en el uso del agua para producción de aceite, expresada en kg m^{-3} se da para un valor de ET_c de 681 mm, mientras que el máximo rendimiento en kg de aceite se alcanza con un valor de ET_c de 916 mm.

Otra conclusión del trabajo Moriana et al. (2003) es que la estrategia de regar sólo en el año de carga no es adecuada, porque el proceso de fructificación requiere de dos estaciones consecutivas y se estaría afectando el número de nudos y de potenciales yemas de flor para el año siguiente.

La relación pulpa-carozo aumenta en condiciones de riego, sin embargo Gucci et al. (2007) reportaron que déficits hídricos leves durante el desarrollo del fruto tiene impacto positivo en dicha relación.

En cuanto al efecto del riego en el contenido de aceite, si bien el estrés hídrico afecta negativamente su producción (Moriana et al., 2003), el porcentaje de extracción de aceite decrece linealmente con el incremento del agua recibida por el cultivo (Grattan et al., 2006). En el mismo sentido Iniesta et al. (2009) reportaron que el estrés hídrico provocado por los tratamientos de riego deficitario continuo (RDC) y riego deficitario regulado (RDR) causó una reducción mayor en el rendimiento de frutos que en el rendimiento de aceite, debido a la mayor concentración de aceite de los frutos correspondiente a los árboles estresados.

En cuanto a la calidad del aceite, el riego no afecta los parámetros básicos que hacen a la clasificación del aceite de oliva virgen pero sí disminuye la concentración de compuestos fenólicos y esto afecta sus propiedades organolépticas resultando en aceites menos amargos y menos agrios (Ahumada-Orellana et al. 2018, Servili et al. 2007).

Para realizar un manejo eficiente del riego, que permita acompasar volumen y frecuencia a los requerimientos del cultivo, es fundamental el conocimiento de la evapotranspiración del cultivo (ET_c). Sin embargo hay que resaltar que la mayoría de los estudios sobre ET, balance hídrico del suelo y respuesta al riego de olivos se han desarrollado en climas áridos y semiáridos, y la aplicabilidad de esos resultados a condiciones climáticas diferentes ha sido cuestionada por algunos autores (Villalobos et al. 2013, Connor 2005).

1.3.2 Métodos para medir o estimar la ET_c

El concepto de evapotranspiración del cultivo (ET_c) engloba la cantidad de agua que vuelven a la atmósfera por evaporación desde el suelo, más la que lo hace a través de los estomas luego de circular por el sistema conductor de la planta. Ambos procesos, evaporación directa y transpiración respectivamente, se dan como respuesta a la demanda evaporativa de la atmósfera, impuesta por las condiciones climáticas.

El requerimiento hídrico de un cultivo es el que compensa la ET_c y el agua retenida en los tejidos. La última representa solo un pequeño porcentaje de la primera cuando se consideran las cantidades correspondientes a todo el ciclo del cultivo.

La dosis de riego (R) cuando se emplee una instalación de riego localizado bien diseñada puede calcularse empleando la siguiente expresión,

$R = ET_c - P_e$

donde: Pe - precipitación efectiva

En los meses en que ET_c - P_e < 0 el agua se acumula como reserva en el suelo; en los meses en que ET_c - P_e > 0 se produce consumo que es necesario suplir bien mediante agua del perfil o bien mediante el riego.

Cuando el contenido de agua en el suelo no es suficiente para reponer la extracción que ocurre en respuesta a la ET_c, el cultivo sufre estrés hídrico y como consecuencia del mismo, se alteran una serie de procesos que se traducen en una reducción en la producción.

Algunos de los métodos para determinar la evapotranspiración son el balance hídrico en parcelas (García Petillo y Castel, 2007) y en lisímetros (Girona et al., 2011), la Eddy covarianza (Paço et al., 2006), el flujo de savia (Moreno et al., 1996) y los sensores remotos (Pôças et al., 2015).

Dentro de los métodos para medir la ET_c, la lisimetría es uno de los más exactos, dado que en el volumen de suelo contenido dentro del lisímetro es posible controlar y medir los diferentes términos que intervienen en el balance (Aboukaled et al., 1981). Sin embargo Allen et al. (2011), ponen énfasis en que las medidas con lisímetros son muy sensibles a los factores ambientales de las zonas que rodean la instalación, debiendo definir claramente las condiciones en las que fueron obtenidos, para una correcta interpretación de los resultados.

Existen varios trabajos de investigación en el ámbito internacional, que han utilizado esta metodología para determinar el consumo de agua (ET_c) en árboles frutales (Girona et al. 2011, 2004, 2002, Johnson et al. 2004, 2000, Ayars et al. 2003, Bryla et al. 2003).

Los lisímetros de pesaje proporcionan datos diarios de evapotranspiración altamente precisos y confiables, pero necesitan de calibraciones periódicas y tienen un costo muy alto. Otro tipo de lisímetros son los de drenaje, en los que el agua de riego en exceso es colectada en el fondo y medida volumétricamente. Una de las principales fuentes de error en estos lisímetros es la debida a los cambios de retención de agua del suelo y al tiempo en que demora la evacuación del agua libre, siendo de especial importancia el registro adecuado de la variación de humedad del suelo contenido en el mismo (Aboukhaled et al., 1981). Estos lisímetros pueden proporcionar valores de ET_c promedio razonables para períodos de tiempo de 7 a 15 días.

Varios investigadores han utilizado lisímetros de drenaje para determinar la ET_c en árboles frutales de hoja caduca (Boland et al. 2000, 1993, Iancu 1997, Stevenson 1989). En los últimos años también se han realizado estudios sobre la evapotranspiración de olivos utilizando lisimetría (Agam et al. 2014, 2013, Ben-Gal 2010).

Debido al costo de los lisímetros así como al tiempo requerido para obtener datos de validez son muy pocos los trabajos que se han realizado en el Uruguay utilizando esta metodología (Capurro et al. 2017, Puppo y García Petillo 2010).

Dado que el riego en olivos, es de historia relativamente reciente, la información disponible sobre necesidades hídricas del olivo, a nivel internacional, surge de estimaciones de ET_c estacionales o de ET_c medida para períodos cortos de tiempo (Orgaz y Fereres, 2008).

Villalobos et al. (2000) estimaron una ET_c promedio anual de 855 mm para un monte cv. Picual con 40 % de cobertura, en Córdoba, España, con un modelo basado en la ecuación de Penman-Monteith combinado con el modelo de evaporación de Ritchie para una amplia serie de datos climáticos (1964-1986). La ET_o promedio anual fue estimada en 1373 mm, un 20 % mayor a la ET_o de la zona donde se realizó nuestro experimento, Estación Experimental INIA Las Brujas, a la que le corresponde un promedio anual de 1132 mm (según registros entre los años 1971-2000). Asimismo Moriana et al. (2003), para la misma localidad y usando el mismo modelo de estimación de la ET_c que los autores anteriores, pero determinando en forma diferente el componente de la evaporación directa, la estimaron en 900 mm. En otras localidades, se reportaron valores similares de ET_c para alcanzar los máximos rendimientos, de 800 a 1000 mm en Trápani, Italia (Baratta et al., 1986) y 950 mm en California (Goldhammer et al., 1994).

El método más utilizado para estimar ET_c es el recomendado por FAO-56 (Allen et al., 1998), que consiste en dos pasos de estimación: se calcula primeramente la evapotranspiración del cultivo de referencia (ET_o) correspondiente a una superficie de cultivo estándar y luego se multiplica por un coeficiente de cultivo (K_c) que tiene en cuenta la especificidad del mismo, de acuerdo a la siguiente ecuación:

$$ET_c = ET_o \times K_c$$

La ET_o tiene en cuenta casi todas las variaciones causadas por el clima (Allen y Pereira, 2009) en el proceso.

Existen dos superficies estandarizadas alternativas para realizar el cálculo:

1) Una gramínea invernal de 12 cm de altura que difiere en su resistencia de superficie según se calcule para un período diario u horario, 70 ó 50 s m^{-1} respectivamente (Allen et al. 2011, 1998).

2) Un cultivo de referencia alto, definido de manera similar a un cultivo de alfalfa de 50 cm de altura, con resistencia de superficie de 45 ó 30 s m^{-1}, según su cálculo sea para un período diario u horario respectivamente (Allen et al., 2011). Este cultivo de referencia y su parametrización en la ecuación de Penman-Monteith (PM) tiende a representar los máximos valores de ET esperados en zonas amplias bien regadas, en condiciones de advección extrema, dado que considera una resistencia de superficie muy baja además de una alta rugosidad.

La ecuación de Penman-Monteith modificada por FAO (PM-FAO), que se presenta a continuación, tiene en cuenta los valores de resistencia de superficie y de resistencia aerodinámica correspondientes al cultivo estándar de la gramínea (Allen et al., 1998), para la estimación con paso diario.

$$ETo = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

donde:

ET_o - evapotranspiración del cultivo de referencia (mm d^{-1})

Rn - radiación neta en la superficie del cultivo (MJ m^{-2} d^{-1})

G - calor sensible desde la superficie al interior del suelo (MJ m^{-2} d^{-1})

T - temperatura media diaria medida a 2 m de altura (ºC)

u_2 - velocidad del viento media diaria medida a 2 m de altura (m s^{-1})

e_s - presión de vapor a saturación (KPa)

e_a - presión de vapor real del aire (KPa)

e_s - e_a - déficit de presión de vapor (KPa)

Δ - pendiente de la curva T- Presión de vapor a saturación (KPa $ºC^{-1}$)

γ - cte psicrométrica del aire (KPa $ºC^{-1}$)

A diferencia de lo que sucede en los climas áridos, en los climas húmedos y sub-húmedos la ET es dominada por la disponibilidad de la radiación neta más que por los fenómenos aerodinámicos del aire. Debido a ello casi no existe diferencia en que la estimación de la ET_c se haga a partir de cualquiera de los dos cultivos de referencia (gramínea o alfalfa), dado que ambos tienen albedos similares en cobertura completa, y por lo tanto similar disponibilidad de energía para el proceso (Allen et al., 2011).

El coeficiente de cultivo (K_c) representa la integración del efecto sobre la ET_c de tres factores: 1) la altura del cultivo, que afecta la rugosidad y la resistencia del pasaje de vapor hacia la atmósfera; 2) la resistencia a la pérdida de agua desde la superficie cultivo-suelo, que está afectada por el área foliar, la fracción del suelo cubierto por el cultivo y el grado de humedad de éste y 3) el albedo de la superficie cultivo-suelo, que es el factor determinante en la radiación neta disponible en superficie, principal fuente de energía en el proceso de evapotranspiración (Allen et al. 2005, Pereira 2004).

El K_c se considera generalmente transferible entre regiones bajo el supuesto de que es casi independiente de las condiciones climáticas de cada zona en particular.

Dado que está ampliamente reconocido que la ecuación de Penman-Monteith modificada por FAO (FAO-PM) permite estimar satisfactoriamente la ET_o, entonces gran parte del éxito de esta forma de estimar la ET_c depende de la rigurosidad en el ajuste del K_c, el cual es específico para un cultivar, marco de plantación y manejo del monte determinados (Villalobos et al. 2013, Allen et al. 1998). El ajuste de este coeficiente se deriva de los estudios que permiten determinar la ET_c, por alguna de las metodologías nombradas anteriormente (balance hídrico en parcelas y en lisímetros, relación de Bowen, Eddy covarianza, flujo de savia y sensores remotos).

Los coeficientes de cultivo se pueden ajustar como K_c medios ó como K_c duales (Hunsaker et al. 2007, 2002, Wright 1982, Jensen et al. 1990), distinguiendo el coeficiente basal del cultivo, K_{cb} y el coeficiente de evaporación, $K_{e.}$

Goldhamer et al. (1994) infirieron un valor de K_c entre 0,65 y 0,85 para montes de olivos maduros en California. Allen et al. (1998) recomendaron valores de K_c de 0,65 para un período inicial y de 0,70 para el resto del año para montes maduros de olivos con 40-60 % de cobertura de suelo. Villalobos et al. (2000) encontraron valores de K_c cercanos a 1 en los meses de invierno y valores entre 0,5 y 0,6 en los meses de verano en montes con 40 % de cobertura al correr un modelo para estimar ET_c con datos climáticos de 1964 a 1986 para Córdoba, España. Los valores más altos estuvieron asociados a aumento de la evaporación directa en la estación lluviosa del clima mediterráneo, en invierno y principio de primavera.

Testi et al. (2006) aplicaron un modelo usando registros climáticos de 20 años, correspondientes a dos sitios diferentes, Córdoba (España) y Fresno (California, USA). El modelo fue validado con medidas de ET_c obtenidas por el método de eddy covarianza. Los valores de K_c promedio anuales inferidos fueron 0,7 y 0,77 para Córdoba, para un monte tradicional de 100 plantas ha^{-1} y otro de 300 plantas ha^{-1}, respectivamente. Mientras que para Fresno los valores de K_c promedio fueron 0,57 y 0,63 según el mayor o menor marco de plantación del monte. Los menores valores de K_c para Fresno con respecto a los de Córdoba son atribuidos por los autores a la menor incidencia de precipitaciones y por tanto a la menor evaporación directa en esa localidad.

Según varios autores (Paço et al. 2006, Pereira et al. 2004) el uso de los K_c medios correspondientes a las distintas etapas del ciclo del cultivo proporciona resultados satisfactorios para cálculos de ET_c promedio para una semana o períodos más largos.

En riegos de alta frecuencia, cultivos con cobertura parcial del suelo (montes frutales y algunos cultivos hortícolas) y regiones con precipitaciones frecuentes, el uso de la metodología de los coeficientes de cultivo duales permite resultados más exactos en la estimación de la ET_c (Allen et al. 2005, Pereira 2004). Esto resulta de gran importancia en el caso de los montes de olivo en los que la gran diversidad de marcos de plantación y prácticas de poda, hace difícil establecer con certeza los valores de K_c reales para cada situación. Asimismo el método de goteo en el riego de olivos genera variaciones espaciales dentro del monte en la humedad de la superficie del suelo, en comparación con otros métodos de riego que humedecen la mayor parte de la superficie del suelo. Debido a estas razones varios autores (Villalobos et al. 2013, Fereres et al. 2011, Orgaz et al. 2006) consideran importante determinar las necesidades de agua del olivo basadas en la separación de los componentes evaporación y transpiración, mediante el ajuste de los coeficientes duales. Aplicando esta metodología el K_c resulta de la suma de dos coeficientes:

$$K_c = K_{cb} + K_e$$

donde:

K_{cb} - coeficiente basal del cultivo

K_e - coeficiente de evaporación del agua del suelo

El K_{cb} es definido como la relación ET_c/ET_o cuando la superficie del suelo está seca y no existe evaporación, pero la transpiración se da a la tasa potencial.

El K_e, describe el componente de evaporación de la ET_c que se da en la fracción húmeda y expuesta del suelo hasta 0,1-0,2 m de profundidad (Z_e). El valor de K_e es máximo luego de un riego o lluvia y decrece a medida que se incrementa el agua evaporada acumulada en Z_e. El valor de este coeficiente nunca puede exceder el

K_c máx (Allen et al., 2005), valor gobernado por la cantidad de energía disponible en la superficie del suelo, limitado a su vez a la fracción del suelo húmeda y expuesta (few). Según Orgaz et al. (2006) el valor de K_e de un monte de olivo regado con riego localizado, depende de los siguientes componentes básicos: 1) lluvia interceptada y directamente evaporada desde la copa del árbol, función del desarrollo de la canopia y de la frecuencia de lluvias, 2) evaporación desde la superficie total del suelo, función del tiempo promedio en el que la superficie del suelo permanece mojada y del desarrollo de la canopia y 3) evaporación desde la superficie mojada por los goteros, que depende de la fracción del suelo mojada por estos y de la frecuencia de riegos.

Bonachela et al. (2001) midieron diariamente la evaporación con microlisímetros de 0,084 m de diámetro interno y 0,12 m de profundidad, previa colocación en el área mojada por el gotero y fuera de la misma. Los datos relevados les permitieron ajustar un modelo para predecir el componente de evaporación (K_e) en la ET_c total del cultivo (K_c). Asimismo Paço et al. (2006) utilizaron la misma técnica de microlisímetros para medir evaporación en un monte de duraznero.

En Uruguay se ajustaron los coeficientes duales para duraznero, separando la evaporación directa del proceso de evapotranspiración a partir de un balance hídrico con paso diario en los 15 cm superiores de la fracción húmeda y expuesta del suelo, siguiendo la metodología presentada en el manual FAO, 56 (Puppo y García Petillo, 2010).

Allen et al. (1998) recomendaron valores de K_{cb} de 0,55 para un período inicial y de 0,65 para el resto del año para montes maduros de olivos con 40-60 % de cobertura de suelo. Para montes de olivo con un porcentaje de cobertura de 25 %, Allen y Pereira (2009) recomiendan el uso de un valor K_{cb} igual a 0.31, mientras que para montes cuyo porcentaje de cobertura fuese entre 30-50 % recomiendan un K_{cb} de 0,51, ambos valores para mediados de temporada (K_{cb} mid). En España, Villalobos et al. (2013) para un huerto de olivos con 49 % de cobertura reportaron un K_{cb} de 0,36 durante el verano (K_{cb} mid), mientras que en Marruecos, Er-Raki et al.

(2010), para un olivar con 60 % se obtuvo un K_{cb} de 0,54, para mediados de la temporada, bajo condición semiárida.

López-Olivari et al. (2016) reportaron valores de K_{cb} para dos años de evaluación, 0,28 y 0,31, para valores de cobertura de 29 y 31 % respectivamente, para la región del Maule, Chile. Ese sitio está ubicado casi en la misma latitud que nuestro estudio pero con condiciones climáticas semiáridas. Los valores de K_e oscilaron entre 0,07-0,21 y 0,09-0,16 para el primero y segundo año respectivamente. El área húmeda por los goteros fue cercana al 4,5 % del marco de plantación, ubicada totalmente debajo de la copa de los olivos.

Para Allen y Pereira (2009), el K_{cb} varía con la altura de los árboles y la cobertura del suelo por la canopia y, en última instancia, con el coeficiente de densidad (K_d, que también está influenciado por la densidad de la canopia (ML) y el cierre estomático (F_r)). El K_{cb} se expresa en términos de un coeficiente de densidad (K_d)

$$K_{cb} = K_{c\,min} + \ K_d\ (K_{cb\,full} - K_{c\,min})$$

donde el $K_{cb\,full}$ es el coeficiente basal máximo y el $K_{c\,min}$ es 0,15 para suelo desnudo en agricultura.

El $K_{cb\,full}$, se estima como:

$$K_{cb\,full} = F_r\left(min(1.0 + 0.1h, 1.2) + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right)$$

siendo el h la altura de los árboles de la etapa correspondiente al $K_{cb\,full}$; u_2 y RH_{min} son los valores promedio de la velocidad del viento (m s^{-1}) y la humedad relativa mínima (%) respectivamente para la etapa donde se alcanza el $K_{cb\,full}$ y F_r es un factor de ajuste del control estomático. Según Allen et al. (1998), F_r se estima como:

$$F_r \approx \frac{\Delta + \gamma(1 + 0{,}34u_2)}{\Delta + \gamma\left(1 + 0{,}34u_2 \frac{r_l}{100}\right)}$$

donde r_l es la resistencia estomática del cultivo (para el olivo 950 s m^{-1} según Allen y Pereira (2009), Δ es la pendiente de la curva de presión de vapor a saturación en función de la temperatura (kPa C^{o-1}) y γ es la constante psicrométrica del aire (kPa C^{o-1}).

El coeficiente de densidad se estima a partir de la fracción del suelo cubierto por la copa (Allen et al., 1998).

$$K_d = \min(1, MLf_{c\,eff,}\, f_{c\,eff}{}^{\left(\frac{1}{1+h}\right)}$$

donde f_{ceff} es la fracción efectiva de suelo cubierta por la canopia o sombreada y ML es un factor que describe la densidad de la canopia o transparencia (para el olivo ML=1,5 según Allen y Pereira (2009) . Para árboles f_{ceff} puede calcularse como sigue:

$$f_{c\,eff} = \frac{f_c}{\mathrm{sen}(\beta)} \leq 1$$

siendo β el ángulo medio del sol sobre el horizonte durante la etapa en la que se alcanza el $K_{cb\ full}$ y se estima como sigue:

$$\beta = arcsen[sen(\emptyset)sen(\delta) + cos(\emptyset)cos(\delta)]$$

donde φ y δ son la latitud y la declinación solar en radianes.

1.3.3 <u>Variación del coeficiente del cultivo con la canopia y con la fracción de intercepción de radiación</u>

Fereres et al. (1981) encontraron una relación para predecir el consumo de agua de árboles jóvenes de almendro, como una proporción del K_c de árboles maduros, a partir del porcentaje de área sombreada. Esta relación confirma que la transpiración es función principalmente de la proporción de luz interceptada por la copa, una vez considerada las características propias de cada especie para oponer resistencia a la transpiración. Es aplicable siempre que exista cobertura parcial, ya sea debido a árboles jóvenes en desarrollo o poda severa de árboles maduros. Esta relación se ha verificado que también se aplica a los huertos de olivos (Fereres et al., 2011).

Asimismo para duraznero, fue reportada una buena correlación del K_c con el porcentaje de intercepción de radiación por la canopia al mediodía (Ayars et al., 2003), lo cual es esencialmente lo mismo que el porcentaje de área sombreada usada por Fereres et al. (1981). Durante este experimento, también se cubrió la superficie del lisímetro con plástico y se ajustó una relación entre un coeficiente de transpiración (K_{cb}) y la radiación interceptada por la copa. Los anteriores autores encontraron que esta única variable explicó bien la variación del K_c y K_{cb} entre años y la variación estacional dentro de una misma temporada.

Según Johnson et al. (2004) el K_{cb} se correlaciona muy bien con el porcentaje de intercepción de radiación por la canopia, pudiendo adoptar una pendiente de 1,5 para predecir el K_{cb} a partir de la intercepción de radiación (en el rango 0 y 70 %) en frutales de hoja caduca. Dado que las medidas de intercepción de radiación requieren el uso de un ceptómetro, no siempre disponible en predios comerciales, los anteriores autores presentan una estimación de la intercepción de radiación a partir de la altura y diámetros del árbol.

Testi et al. (2004), trabajando con olivo, propusieron una relación lineal simple entre % de área sombreada y K_c promedio de los meses de verano, válido para % de área sombreada mayor a 25 % con su variación debida a las manchas de suelo húmedo con riego localizado, no sirve para períodos con lluvias.

Girona et al. (2011) determinaron la relación del K_c con la intercepción de la canopia en pera y manzana. La ET_c fue medida en lisímetros y la intercepción de radiación al mediodía fue determinada en una base semanal.

1.4 HIPÓTESIS DE TRABAJO

Si bien existe abundante información de riego en olivos para climas áridos a nivel internacional, la misma es muy escasa para climas sub-húmedos como el de Uruguay. Una de las principales dudas con respecto al manejo del riego de olivos en áreas húmedas es si los patrones de demanda de agua (ET_c) son similares a los obtenidos en zonas semiáridas, básicamente porque el olivo presenta claros mecanismos de regulación del agua dependiendo de la situación climática-ambiental en la que se encuentre. Estas dudas son aún mayores cuando se trabaja con plantas jóvenes.

Dado que en un monte particular, la intercepción de radiación solar por la copa del árbol es uno de los factores que más incide en el valor del K_c (Girona et al. 2011, Ayars et al. 2003), las medidas de este parámetro podrían usarse para ajustar los $K_{cy/o}$ K_{cb} específicos.

En base a lo anterior se plantearon las siguientes hipótesis: 1) la demanda de agua de árboles jóvenes plantados en climas húmedos puede ser diferente a la demanda analizada en árboles adultos de climas áridos y 2) el coeficiente basal del olivo se puede estimar a partir de la intercepción de la radiación solar por la copa del árbol al mediodía.

1.5 OBJETIVOS

El objetivo general de este estudio fue determinar la evapotranspiración de árboles jóvenes de olivo en Uruguay y a partir de ella generar información que permita ajustar el riego, con la finalidad de promover un uso racional y sostenible tanto del agua como de la energía durante esta etapa del cultivo.

Con la finalidad de mejorar las estimaciones de ET_c para una amplia gama de condiciones de producción de olivos, se eliminó el componente de evaporación del suelo de la evapotranspiración total del cultivo y se derivó el coeficiente del cultivo basal (K_{cb}) para las condiciones climáticas húmedas de Uruguay. Se exploró el desarrollo de una herramienta predictiva para K_{cb} que se pueda usar en la gestión del riego. Se exploraron dos opciones de modelado: 1) expresando K_{cb} en función del día del después del inicio del crecimiento (DPGI); 2) relacionando K_{cb} con la intercepción de la luz del mediodía por la copa.

Se publicaron dos artículos donde se abordaron los objetivos planteados.

En el primer artículo: "Determination of young olive-tree water consumption with drainage lysimeters", publicado en Journal of Water Resource and Protection (2014), Vol. 6, pág. 841-851 se describe en forma pormenorizada la metodología empleada, se aborda el objetivo general de determinar la evapotranspiración a lo largo del ciclo del cultivo y se ajustan las primeras relaciones entre el coeficiente de cultivo (K_c) de los meses de verano con el tamaño de los árboles.

En el segundo artículo: "Seasonal basal crop coefficient pattern of young non-bearing olive trees grown in drainage lysimeters in a temperate sub-humid climate", publicado en Agricultural Water Management 226 (2019) 105732, se abordó el objetivo específico de separar la evaporación directa del proceso de evapotranspiración, se ajustó el coeficiente basal del cultivo (K_{cb}) y se modeló en función de dos variables con la finalidad de definir una herramienta para la gestión del riego.

Determination of Young Olive-Tree Water Consumption with Drainage Lysimeters

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Abstract

Information about olive-tree irrigation in sub-humid climates, as in Uruguay, is scarce. Water consumption of young olive trees, Arbequina variety, was measured for two years with six drainage lysimeters, protected from rain by an automatic rain-out shelter. Irrigation water volume and drainage of each lysimeter were measured daily and soil moisture was registered twice a week with neutron probe at four depths. Evapotranspiration (ETc) was calculated by volume balance. Data periods when available water descended below 50% or increased over 100% were eliminated, as those in which the stem water potential was below −1.5 MPa. Water consumption values were averaged within 7- to 14-day periods, expressed in mm·d^{-1}, and referred to a 2.5 × 5.5 m plantation framework without vegetation cover. There was a positive linear relation of the summer crop coefficient (Kc mid) with age, canopy cover percentage and canopy volume. Canopy cover percentage was the parameter which explained most of the variation of Kc mid, which ranged between 0.13 and 0.24, with 5% and 46% canopy cover, respectively. Full irrigation, associated to a good drainage resulted in a rapid growth of the young plants, bringing forward the start of full production period. This represents useful information for the adjustment of irrigation in olive-tree orchards, to accelerate growth with a rational and sustainable use of both water and energy in Uruguay.

Keywords

Evapotranspiration, Crop Coefficients, Irrigation Requirements, *Olea europea* L.

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1. Introduction

The olive tree is traditionally grown in rainfed conditions in a Mediterranean climate. However, there are several studies proving that this crop has a good response to irrigation, as it enhances young plant growth, increases adult plant olive production in weight [1]-[3], and shows a rapid adaptation in the transition from a rainfed to an irrigated system [4].

An important expansion of olive-tree production began in Uruguay in 2003. With a sustained increase, the cultivated area has now reached 9000 hectares, according to the Uruguayan Olive-tree Association [5]. Most of the information regarding olive trees has been generated in arid or semi-arid climates, while there is scarce information for this crop in sub-humid climates, as Uruguay. Generation of local knowledge on crop evapotranspiration (ETc) is crucial for an efficient irrigation management, which would enable fitting irrigation volume and frequency to crop requirements.

ETc can be determined exactly with the use of lysimeters [6]. It is possible to adjust crop coefficients (Kc) using this data and that of the reference evapotranspiration (ETo) obtained from weather data supplied by a nearby climate station. The use of these coefficients enables to estimate ETc with a simple method of double step estimation: first ETo is calculated using climate parameters; then it is multiplied by Kc to consider crop specificity (ETc = ETo × Kc). The Penman Monteith-FAO equation (ETo-PM) gives a rather accurate estimation of ETo. Therefore, estimating ETc successfully with this double step method depends greatly on the accuracy of the Kc adjustment, which varies according to species, developmental stage and orchard management [7].

The aim of our study was to generate information regarding olive-tree water consumption in Uruguay allowing irrigation adjustment, in order to promote a rational and sustainable use of both water and energy.

2. Materials and Methods

Six drainage lysimeters (1.9 × 0.9 × 1.35 m depth) were located in the National Agriculture Research Institute, INIA-Las Brujas Experimental Station (34°40'S; 56°20'W). These devices were protected from rain by a rain-out shelter, which would close automatically every time rain exceeded 3 mm.

In each lysimeter an olive tree (*Olea europea* L. cv. Arbequina) of different age and size was planted. We measured the water consumed by the plants during two seasons: 2010-2011 and 2011-2012. Lysimeters #1 and #12 had plants brought directly from nursery; lysimeters #2 and #11 got 2-yr-old plants; and lysimeters #3 and #10 got 4-yr-old plants (**Figure 1**). Grown plants were obtained from a commercial orchard.

Lysimeters were surrounded by irrigated crops to avoid an "oasis" effect as a consequence of advective processes, alternating oat and wheat in the first and second winters, respectively with sorghum in summer. The separation between lysimeters with olive trees simulated a plantation framework of 2.5 × 5.5 m (**Figure 1**).

The lysimeters were backfilled in layers, following the local profile horizons sequence and respecting bulk density corresponding to each horizon. The soil profile consisted of a sequence of four horizons (0 - 0.20 m; 0.20 - 0.40 m; 0.40 - 0.60 m and >0.60 m), mainly silty clay loam texture, described in detail in a previous work [8].

Each lysimeter was irrigated with three self-compensating drippers (4 $L \cdot h^{-1}$ per emitter) located in line spaced at 0.63 m (**Figure 1**). Excessive irrigation prior to the evaluation period assured that the whole backfilled soil had a water content corresponding to field capacity (FC). Irrigation management was adjusted so as to produce a slight drainage within the lysimeters with the largest plants, which would imply non-limiting water content in all of them.

Soil moisture corresponding to FC was determined for each horizon in a lysimeter without vegetation. There the soil was saturated with water, covered with a polyethylene film and left to drain for four days. Following, two soil samples of each depth were taken to determine soil moisture by the gravimetric method. Values were averaged for each horizon. Soil moistures corresponding to permanent wilting point (PWP) was estimated using Equation (1), which has been calibrated for Uruguayan soils [9]:

$$\text{PWP} = -5 + 0.74 \times \text{FC} \tag{1}$$

where FC is field capacity (percent dry weight).

Soil water content variation in backfilled soil of each lysimeter was measured with a neutron probe (model 503 DR Hydroprobe). A 1-meter aluminum access tube was installed in each lysimeter to monitor soil moisture through the whole depth. This tube was located 0.20 m from the surface drip line (orthogonally), and at an equal

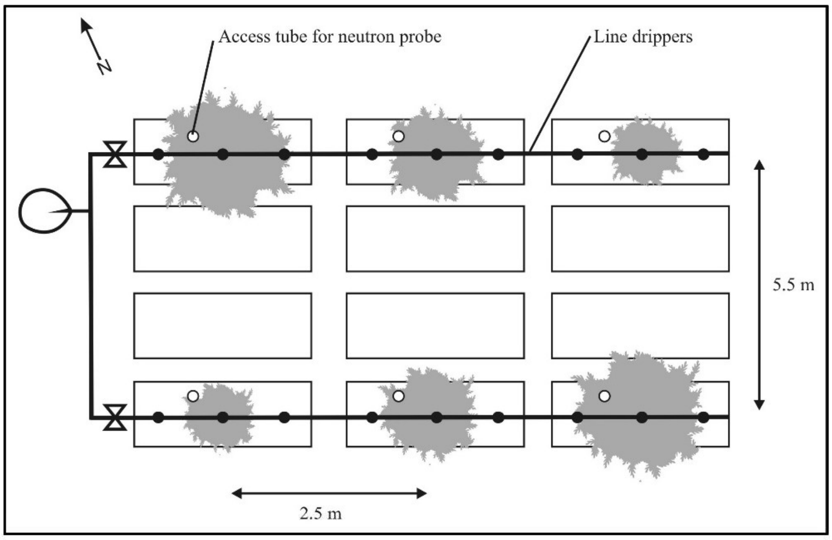

Figure 1. Schematic presentation of the lysimeter disposition, irrigation equipment, and access tubes for a neutron probe.

distance from the two nearest emitters (Figure 1). Measurements at the depths 0.20; 0.40; 0.60 and 0.80 m, were conducted twice a week, before irrigation, following published methodology [10]-[12]. The neutron probe was calibrated with the gravimetric method for each measured depth and then multiplied by bulk density to obtain volumetric moisture content [13]. Irrigation and drainage water volumes in each lysimeter were recorded on a daily basis. There were no rain entries due to the rain-out shelter.

ETc was calculated by water volume balance following Equation (2):

$$\mathrm{ETc} = \mathrm{I} - \mathrm{D} \pm \Delta\mathrm{Hs} \tag{2}$$

where ETc is real olive-tree evapotranspiration; I is irrigation; D is drainage and ΔHs is soil moisture variation.

Stem water potential (ψ stem) was measured with a Scholander pressure chamber [14], on clear days every fortnight at noon, during months of maximum atmospheric demand, to contrast the appropriate plant water status. Each date, two small branches of the current year per tree were measured. These branches were selected from the sunny periphery and located in the mid height of the canopy [15] [16].

Longitudinal and transversal diameters and upper and lower canopy heights were measured with a ruler every three months. The area corresponding to the horizontal canopy projection was calculated as a circle and the canopy volume as a sphere.

Periods of water consumption which met the following criteria were eliminated:

1) Available water descended below 50%. This is a safe criterion since it is stated in the literature that it is possible to allow 75% of available water depletion without stomatal adjustment [17]. Decrease in soil moisture in the first 0.20 m was not considered for this study, since water in this depth may be lost by evaporation, independently from crop water consumption [18].

2) Lysimeters drainage was obstructed and available water increased over 100%.

3) ψ stem values were below −1.5 MPa. There are references in the literature of normal ψ stem values for irrigated trees within the range −0.8 to −2.0 MPa [15] [19].

4) Plants showed stress symptoms. 4-yr-old plants suffered leaf drop immediately after transplant in the lysimeters. The plant in lysimeter #10 recovered by 21st December 2010, while the plant in lysimeter #3 never reached an optimum foliage density, and was therefore eliminated from the evaluation process.

ETo was calculated with ETo-PM [7], using daily climate data provided by the INIA-Las Brujas Experimental Station located 500 m from the experiment. Water consumption values, ETc $\mathrm{L \cdot d^{-1}}$, were averaged within 7- to 14-day periods, due to changes in soil water retention [6] [20]. These values were expressed in $\mathrm{mm \cdot d^{-1}}$, and referred to a 2.5 × 5.5 m plantation framework without vegetation cover.

The crop coefficient corresponding to summer months (Kc mid) was adjusted as the ratio between ETc (in mm·d^{-1}) and ETo-PM, from 21st December to 21st March. The functions of plant water consumption (in L·d^{-1}) and Kc mid were adjusted with: age of trees, canopy cover percentage (horizontal projection of the canopy divided by the plantation framework of 2.5 × 5.5 m) and canopy volume (in m^3).

3. Results and Discussion

3.1. Soil Water Content

Soil water parameters of the lysimeters' backfill indicate a similarity among available water storage capacities of all the horizons (Table 1).

Figure 2 shows the neutron probe calibration for the four measured depths. Volumetric soil moisture and relative count (ratio) showed a linear relation with determination coefficients which ranged from 0.66 to 0.80.

Discrete measurements of soil moisture are shown as continuous lines to facilitate their visualization (Figure 3 and Figure 4). The irrigation strategy sought to maintain soil moisture at FC in the following depths: 0.40, 0.60 and 0.80 m. Within the first 0.20 m, water may have been lost due to evaporation independently from the crop water consumption [18].

Monitoring soil moisture allowed discarding data of periods in which available water descended below 50% in any of the following depths: 0.40, 0.60 and 0.80 m. This occurred in lysimeter #2 from November 22, 2010 to February 25, 2011 (Figure 3) and in lysimeter #10 from February 22 to April 4, 2011 and November 5 to 12, 2012 (Figure 4). The rapid increase in the water consumption rate of these plants, due to a higher canopy density, produced a fast decline in soil moisture, which was difficult to revert given the low irrigation rate applied by the drippers.

Lysimeter #1 had the period from February 23 to April 2, 2012 discarded (Figure 3), since a temporal drainage obstruction saturated the soil, increasing soil moisture over 100% available water. There was no need to discard data periods of lysimeters #11 and #12, where the soil moisture was successfully maintained close to FC, making sure the plants developed under proper water availability conditions.

3.2. Stem Water Potential

All stem water potential measures ranged from −0.4 to −1.2 MPa. Values within this range have been cited as corresponding to plants in good water status conditions [3] [15] [19], therefore there was no need to discard periods based on these measures.

3.3. Vegetative Growth

Figure 5 shows plant size expressed as the area of the horizontal projection and canopy volume reached in summer of both evaluated seasons.

In their transition from 3 to 4 years old, the intermediate plants duplicated their canopy area and quintupled their canopy volume; while the largest plant (lysimeter #10) increased its canopy area 40%, and its canopy volume 50% in its transition from five to six years old (Figure 5). This important growth took place under non-water-limiting and good-drainage conditions.

Important increase in canopy volume in well irrigated trees compared to trees under continuous deficit irrigation (CDI) and under regulated deficit irrigation (RDI) has been reported before [11].

Table 1. Soil water parameters of lysimeter backfill: Field Capacity (FC); Permanent Wilting Point (PWP) and Available Water (AW).

Depth (cm)	FC (cm^3·cm^{-3})	PWP (cm^3·cm^{-3})	AW (cm^3·cm^{-3})
0 - 20	0.41	0.24	0.17
20 - 40	0.38	0.21	0.17
40 - 60	0.40	0.23	0.17
>60	0.39	0.22	0.17

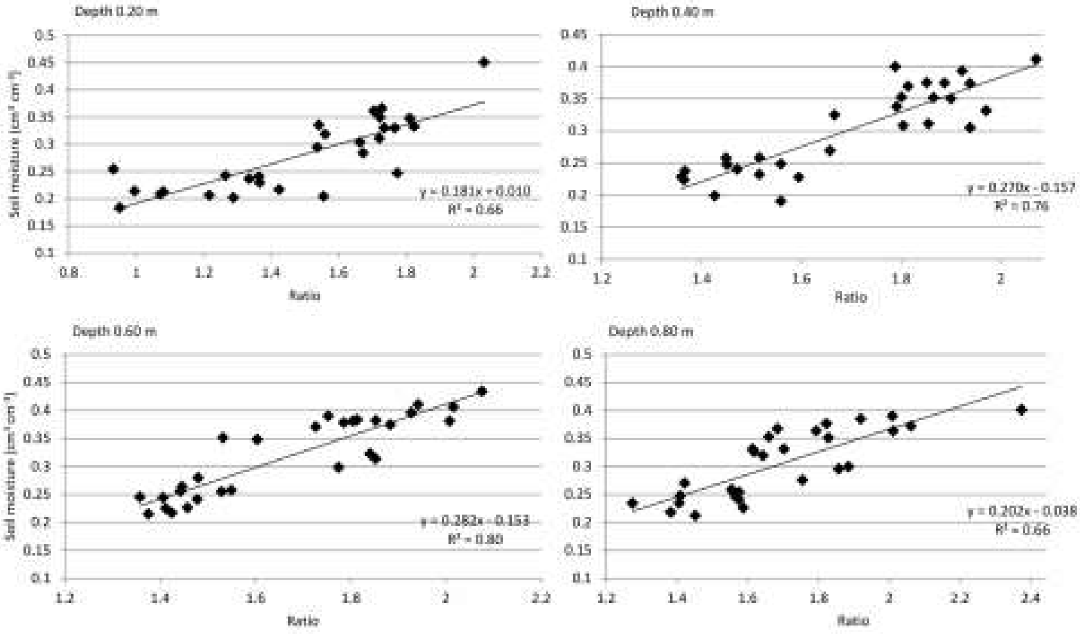

Figure 2. Neutron probe calibration curves with gravimetric method.

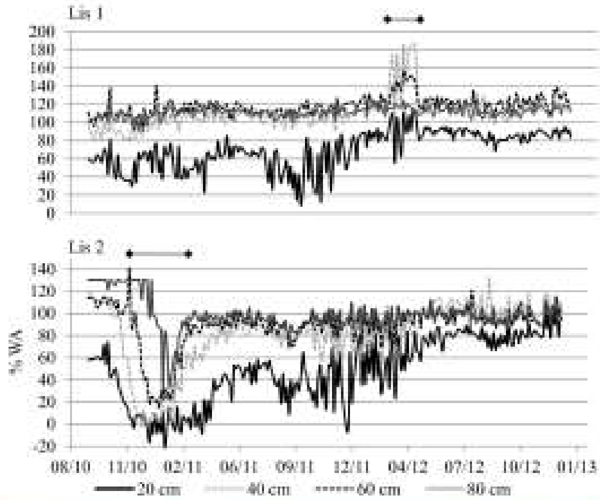

Figure 3. Backfill soil moisture in lysimeters #1 and #2, expressed as a percentage of available water in four different depths. ⟷ Discarded periods due to soil moisture deficits or excesses.

The largest plant (lysimeter #10) suffered total defoliation immediately after transplant and it slowly recovered during summer, the first evaluation season. Because of this, one of the intermediate plants which was 4 years old in the second evaluation year reached a larger canopy size in area and volume than this 5-yr-old plant in lysimeter #10 (**Figure 5**).

3.4. Water Consumption

Water consumption in $L \cdot d^{-1}$ of all five plants followed the same seasonality pattern as the atmospheric demand

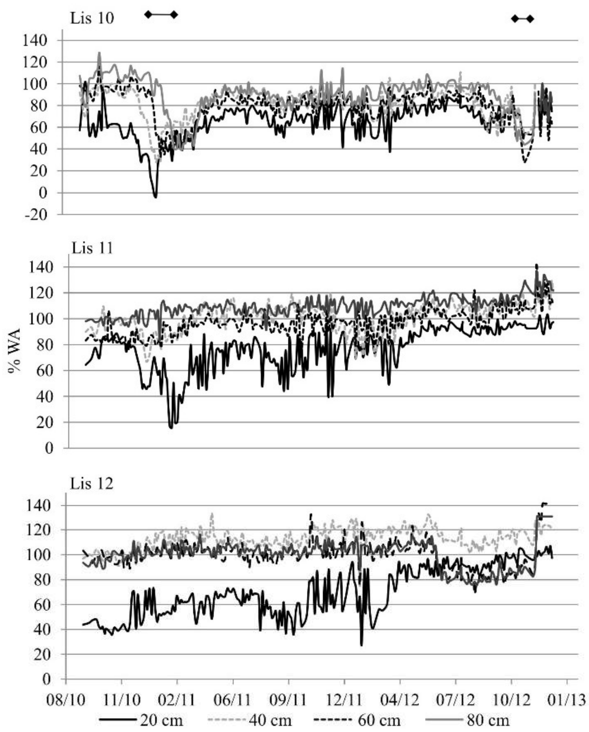

Figure 4. Backfill soil moisture in lysimeters #10, #11 and #12, expressed as a percentage of available water in four different depths. ◆—◆ Discarded periods due to soil moisture deficits or excesses.

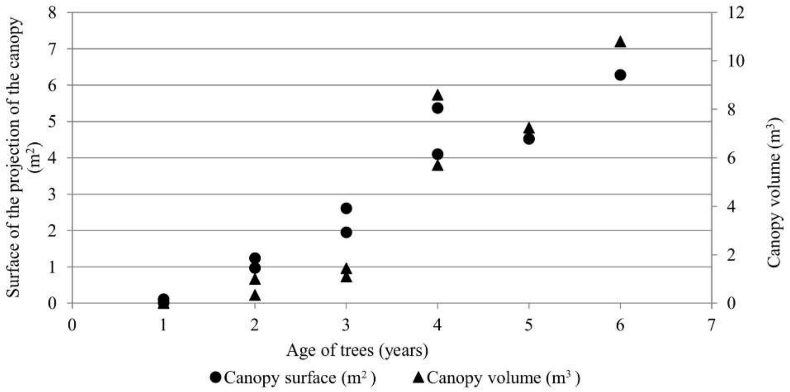

Figure 5. Relation between plant size (expressed both as projected area in m^2-circles- and as canopy volume in m^3-triangles-) and age of trees.

(ETo), recording the maximum values during December, January and the first fortnight of February (summer in Southern Hemisphere), while the minimum values were recorded during June, July and August (**Figure 6**).

The smallest plants reached their maximum water consumption of 12 and 13 $L \cdot d^{-1}$ during January 2011 in the first evaluation season. The following season, the maximum water consumption values of the same plants, also reached in January, were 16 and 18 $L \cdot d^{-1}$. The atmospheric demand (ETo) in January was c.a. 7 $mm \cdot d^{-1}$ in both seasons (**Figure 6**).

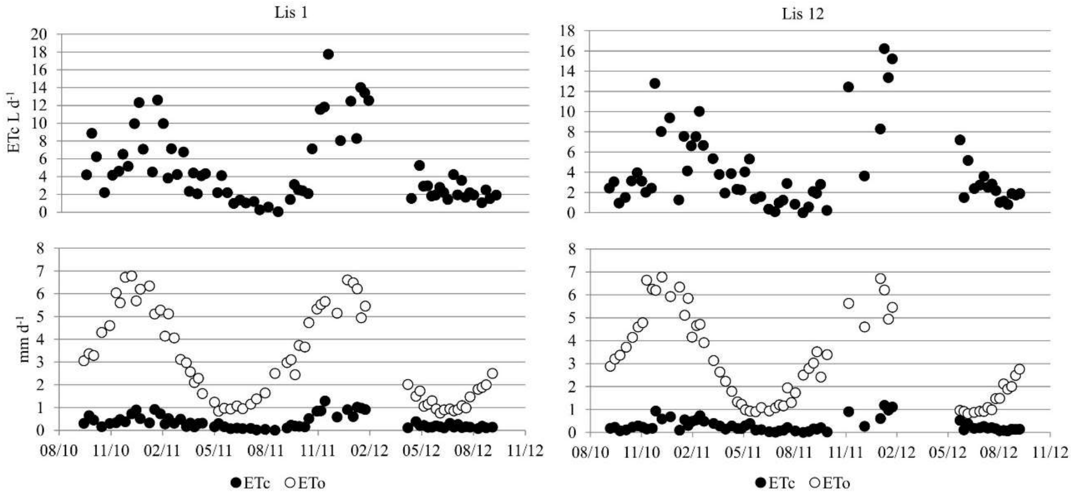

Figure 6. Water consumption in L·d^{-1} of the two smallest plants, located in lysimeters #1 and #12 (above). ETo and ETc of the 2.5 × 5.5-m framework without vegetation cover (below).

The intermediate plants, in lysimeters #2 and #11, had maximum water consumption values of 14 and 13 L·d^{-1}, respectively, in the first season; and of 27 and 24 L·d^{-1} respectively, in the second season (**Figure 7**). These consumption differences respond to differences in plant size, being the olive tree in lysimeter #2 larger than that in lysimeter #11, in the second evaluation season it presented 30% more area and 50% more canopy volume (4-yr-old plants in **Figure 5**).

The largest plant presented in January a maximum consumption of 19 L·d^{-1} in the first evaluation season and of 30 L·d^{-1} in the second one. As mentioned earlier, data of this olive tree corresponding to the period prior to 21st December 2010 was eliminated due to post-transplant defoliation.

Summer water consumption was analyzed relative to age of trees, canopy cover percentage, and canopy volume (**Figure 8**). The maximum water consumption included in the regression was the average of the summer month values of each plant each season. A significant positive linear relation was found ($p < 0.01$).

Canopy cover percentage was the parameter to explain most of the variation of plant water consumption (R^2 = 0.85). Tree height, involved in the canopy volume calculation, did not improve the explanation to this variation. According to some authors, water consumption in humid and sub-humid climates should be more influenced by the net available radiation and its interception by the canopy, than by the aerodynamic phenomena which are enhanced by plant height [21].

3.5. Maximum ETc and Kc Mid

As in the case of water consumption, ETc of all five evaluated plants (referred to the 2.5 × 5.5-m framework without vegetation cover) followed the same seasonality than ETo, recording the maximum values during December, January and the first fortnight of February, while the minimum values were recorded during June, July and August.

Both small plants had a maximum ETc slightly over 1.2 mm·d^{-1} in the second season (**Figure 6**). A similar value, 1.29 mm·d^{-1}, has been reported for plants with the same features of age, cover percentage and interrow management; and with similar ETo values [22].

The maximum ETc values of the intermediate plants in the second season were 2 mm·d^{-1} and 1.7 mm·d^{-1}, corresponding to lysimeters #2 and #11, respectively (**Figure 7**). These values were slightly lower than those reported in the literature for plants which were one year younger (3 yrs old) and had a lower cover percentage than our plants [22].

Some authors have stated that ETc determinations conducted in small areas surrounded by lower green crops should not be extrapolated to large areas with the same crop [21]. Generally, research papers report adult orchard data [23] [24]. However, one of the few papers that do report ETc values for young olive orchards with similar

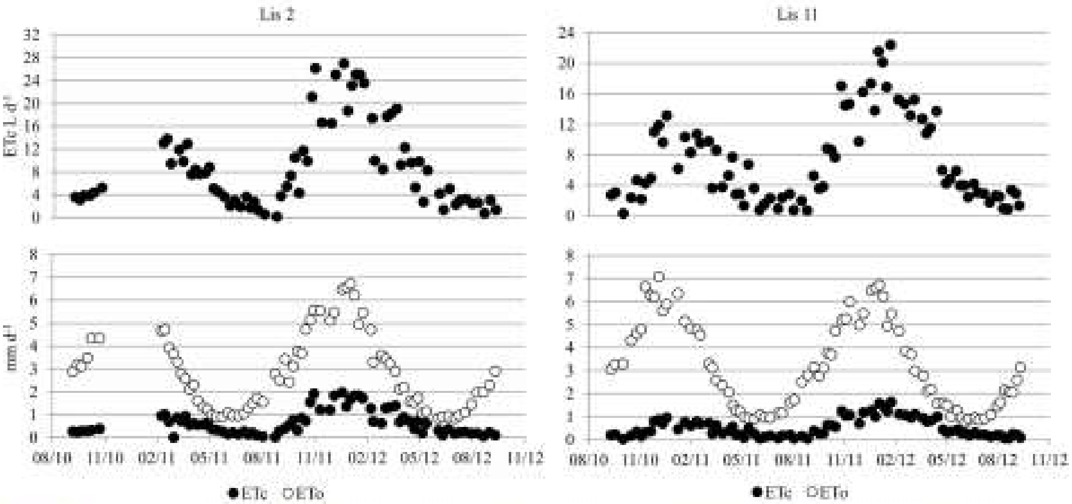

Figure 7. Water consumption in L·d^{-1} of the two intermediate plants, located in lysimeters #2 and #11 (above). ETo and ETc of the 2.5 × 5.5-m framework without vegetation cover (below).

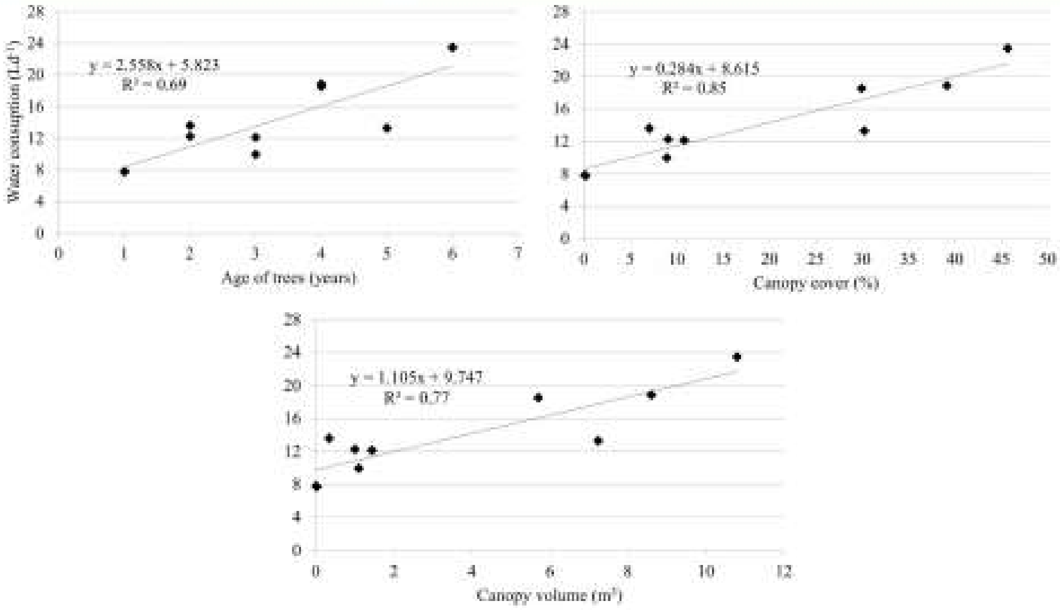

Figure 8. Maximum plant water consumption in L·d^{-1} plotted against age of trees, canopy cover percentage (within a 2.5 × 5.5-m plantation framework), and canopy volume.

atmospheric demands to those recorded in our study [22], got similar ETc values to ours. This would imply that even if the installation of the lysimeters was not within an olive orchard of the same age, differences in aerodynamic phenomena may have played a minor role in determining ETc in our young plants.

The maximum ETc value of the largest plant in the second season was 2.2 mm·d^{-1} (Figure 9).

Kc mid used for the regression was the average of the summer month values of each plant each season. There was a significant ($p < 0.01$) positive linear relation of Kc mid with age of trees, canopy cover percentage in the plantation framework, and canopy volume. Canopy cover percentage was the parameter to explain most of the variation of Kc mid (Figure 10).

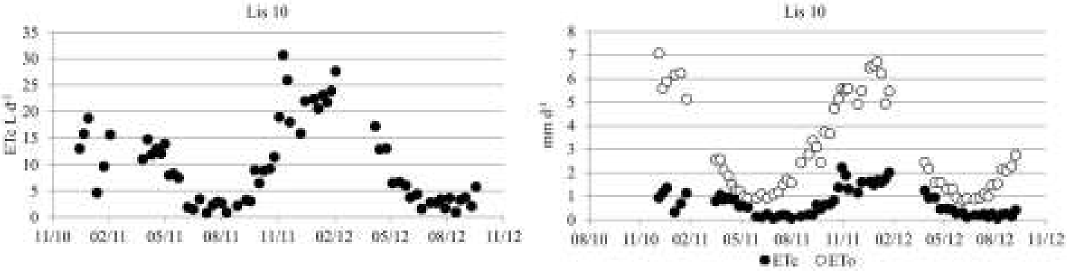

Figure 9. Water consumption in L·d^{-1} of the largest plant, located in lysimeter #10 (left). ETo and ETc of the 2.5 × 5.5-m framework without vegetation cover (right).

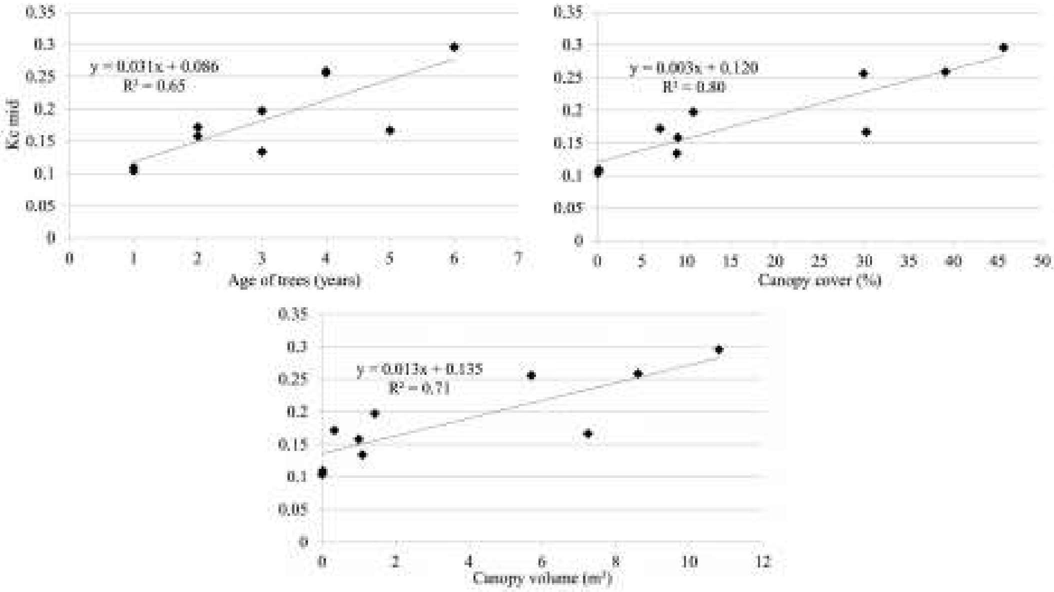

Figure 10. Summer crop coefficient (Kc mid) for the plantation framework 2.5 × 5.5 m relative to age of trees, canopy cover percentage in the plantation framework, and canopy volume in m^3.

Other authors who have studied different fruit trees agree that the proportion of canopy intercepted light at midday, which essentially coincides with the percentage of shaded area, explains well both seasonally and yearly Kc variations [25]-[27].

A similar relation has been found between the percentage of shaded area and averaged Kc of the summer months, in young orchards with a shaded area below 25% and in dry periods [22]. Our estimation for an orchard with 5% cover (small plants in their first evaluation year) corresponded to a Kc mid value of 0.14, similar to the 0.15 Kc value reported in the work cited above. Kc mid value for 46% cover, the maximum cover percentage reached by our large plant, was 0.29. This value was lower than a reported value for Córdoba, Spain, of 0.40, which had been adjusted with a simulation model [24]. This difference could be related to the relative impact of climate on Kc mid, presenting higher values for Córdoba's arid summer, compared to lower values in a more humid climate, as in Uruguay. This effect grows stronger as the crop height increases [7] [18].

4. Conclusions

This is one of the first studies in the world using lysimeters to measure water consumption of olive trees. Results of evapotranspiration and Kc mid presented herein are representative of young orchards, where radiation received by plants is not affected by shading of contiguous plants, and where aerodynamic phenomena influence each plant individually.

A positive linear relation was found between Kc mid (adjusted for the 2.5 × 5.5-m framework without vegetation cover) and canopy cover percentage. This relation is only valid for dry periods, on silty clay loam soils, with drip irrigation, and in orchards whose canopy cover does not exceed 46%.

Water consumption in $L \cdot d^{-1}$ was strongly related to plant size. Canopy cover percentage was the variable to explain most of the variation in plant water consumption.

Full irrigation associated to good soil drainage resulted in a rapid growth of young plants. In one growth season, in their transition from 3 to 4 years old, intermediate plants duplicated their canopy area and quintupled their canopy volume. The larger plant increased the canopy area and canopy volume an average of 36% and 40%, respectively, in its transition from five to six years old. This rapid growth would accelerate the orchard's entrance into full production, reaching it at a younger age.

In order to be able to separate the evapotranspiration into its two components: transpiration and direct evaporation from the soil, this study should be continued for at least another year. This is the information needed to enable the adjustment of Kcb and Ke coefficients, which, alongside with Kcb adjustment with the percentage of canopy radiation interception, will offer useful information to estimate ETc. Hence, it may be applied to a broader range of agriculture systems, including different plantation frameworks, as well as different wetting patterns caused by variations in a number of drippers per plant, water volume and/or spacing between drippers. However, the use of this information should be restricted to plants when they are young.

References

[1] Fernández, J.E. and Moreno, F. (1999) Water Use by Olive Tree. *Journal of Crop Production*, **2**, 101-162. http://dx.doi.org/10.1300/J144v02n02_05

[2] Girona, J., Luna, M., Arbonés, A., Mata, M., Rufat, J. and Marsal, J. (2002) Young Olive Trees Responses (*Olea europaea* L. Cv. Arbequina) to Different Water Supplies. Water Function Determination. *Acta Horticulturae*, **586**, 277-280.

[3] Moriana, A., Orgaz, F., Pastor, M. and Fereres, E. (2003) Yield Responses of a Mature Olive Orchard to Water Deficits. *Journal of the American Society for Horticultural Science*, **128**, 425-431.

[4] Alegre, S., Marsal, J., Mata, M., Arbonès, A. and Girona, J. (2002) Regulated Dedicit Irrigation in Olive Trees (*Olea europaea* L. Cv. Arbequina) for Oil Production. *Acta Horticulturae*, **586**, 259-262.

[5] Asolur (2013). http://www.asolur.org.uy/contacto.html

[6] Aboukhaled, A., Alfaro, A. and Smith, M. (1982) Los Lisímetros. *Irrigation and Drainage Paper* 39, FAO, Roma.

[7] Allen, R., Pereira, L.S., Raes, D. and Smith, M. (1998) Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. *Irrigation and Drainage Paper* 56, FAO, Rome.

[8] Casanova, S. (2008) Morfosiologia da cultura de batata submetida a diferentes regimes hídricos. Dissertaçao, Curso de Mestrado da Universidade Federal de Santa María, Brasil.

[9] Silva, A., Ponce De León, J., García, F. and Durán, A. (1988) Aspectos metodológicos en la determinación de la capacidad de retener agua de los suelos del Uruguay. Facultad de Agronomía, Boletín de Investigación, No. 10.

[10] García Petillo, M. and Castel, J.R. (2007) Water Balance and Crop Coefficient (Kc) Estimation of a Citrus Orchard in Uruguay. *Spanish Journal of Agricultural Research*, **5**, 232-243. http://dx.doi.org/10.5424/sjar/2007052-243

[11] Iniesta, F., Testi, L., Orgaz, F. and Villalobos, F.J. (2009) The Effects of Regulated and Continuos Deficit Irrigation on the Water Use, Growth and Yield of Olive Trees. *European Journal of Agronomy*, **30**, 258-265. http://dx.doi.org/10.1016/j.eja.2008.12.004

[12] Morales, P., García Petillo, M., Hayashi, R. and Puppo, L. (2010) Respuesta del duraznero a diferentes patrones de aplicación de agua. *Revista Brasileira de Engenharia Agrícola e Ambiental*, **14**, 17-24. http://dx.doi.org/10.1590/S1415-43662010000100003

[13] Haverkamp, R., Vauclin, M. and Vachaud, G. (1984) Error Analysis in Estimating Soil Water Content from Neutron Probe Measurements: 1. Local Standpoint. *Soil Science*, **137**, 78-90. http://dx.doi.org/10.1097/00010694-198402000-00002

[14] McCutchan, H. and Shackel, K.A. (1992) Stem Water Potential as a Sensitive Indicator of Water Stress in Prune Trees (*Prunus domestica* L. Cv. French.). *Journal of the American Society for Horticultural Science*, **117**, 607-611.

[15] Sellés, G., Ferreyra, R., Sellés, I. and Lemus, G. (2006) Efecto de diferentes regímenes de riego sobre la carga frutal, tamaño de fruta y rendimiento del olivo cv. Sevillana. *Agricultura Técnica* (*Chile*), **66**, 48-56.

[16] Sellés, G., Ferreyra, R. and Maldonado, P. (2002) Cámara de presión. www.olivos.cl/blog/camara-de-presion

[17] Orgaz, F. and Fereres, E. (2008) Riego. In: *El cultivo del olivo*, 6ª Edition, Ediciones Mundi-Prensa y Junta de Andalucía, Madrid, 336-362.

[18] Pereira, L.S. (2004) Necessidades de Água e Métodos de Rega. Publicações Europa-América, Lisboa,.

[19] Moriana, A. and Fereres, E. (2002) Plant Indicators for Scheduling Irrigation of Young Olive Trees. *Irrigation Science*, **21**, 83-90. http://dx.doi.org/10.1007/s00271-001-0053-8

[20] Puppo, L. and García Petillo, M. (2010) Determinación del consumo hídrico del duraznero mediante lisimetría de compensación con napa freática constante. *Revista Brasilera de Engenharia Agricola e Ambiental*, **14**, 25-31. http://dx.doi.org/10.1590/S1415-43662010000100004

[21] Allen, R., Pereira, L.S., Howell, T.A. and Jensen, M.E. (2011) Evapotranspiration Information Reporting: I. Factors Governing Measurement Accuracy. *Agricultural Water Management*, **98**, 899-920. http://dx.doi.org/10.1016/j.agwat.2010.12.015

[22] Testi, L., Villalobos, F.J. and Orgaz, F. (2004) Evapotranspiration of a Young Irrigated Olive Orchard in Southern Spain. *Agricultural and Forest Meteoroly*, **121**, 1-18. http://dx.doi.org/10.1016/j.agrformet.2003.08.005

[23] Goldhamer, D.A., Dunai, J. and Ferguson, L.F. (1994) Irrigation Requirements of Olive Trees and Responses to Sustained Deficit Irrigation. *Acta Horticulturae*, **356**, 172-175.

[24] Villalobos, F.J., Orgaz, F., Testi, L. and Fereres, E. (2000) Measurement and Modeling of Evapotranspiration of Olive (*Olea europaea* L.) Orchards. *European Journal of Agronomy*, **13**, 155-163. http://dx.doi.org/10.1016/S1161-0301(00)00071-X

[25] Ayars, J.E., Johnson, R.S., Phene, C.J., Trout, T.J., Clark, D.A. and Mead, R.M. (2003) Water Use by Drip-Irrigated Late-Season Peaches. *Irrigation Science*, **22**, 187-194. http://dx.doi.org/10.1007/s00271-003-0084-4

[26] Girona, J., Del Campo, J., Mata, M., López, G. and Marsal, J. (2011) A Comparative Study of Apple and Pear Tree Water Consumption Measured with Two Weighing Lysimeters. *Irrigation Science*, **29**, 55-63. http://dx.doi.org/10.1007/s00271-010-0217-5

[27] Johnson, R.S., Ayars, J.E., Trout, T.J., Mead, R. and Phene, C. (2000) Crop Coefficients for Mature Peach Trees Are Well Correlated with Midday Canopy Light Interception. *Acta Horticulturae*, **537**, 455-460.

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Seasonal basal crop coefficient pattern of young non-bearing olive trees grown in drainage lysimeters in a temperate sub-humid climate

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ABSTRACT

Young non-bearing olive trees were grown in drainage lysimeters and their water consumption was measured over two consecutive yearly-experimental periods to analyze the effect ofseasonal variations on the basal crop coefficient (K_{cb}). Micro-lysimeter measurements were used to quantify soil evaporation (E_s) and E_s was subtracted from evapotranspiration (ET_c) to determine transpiration. Monthly mean (K_{cb}) were determined as (ET_c-E_s)/ET_o, where ET_o is the FAO-PM grass-reference evapotranspiration, calculated from locally measured weather data. The observed K_{cb} value at mid-season, 0.38, was obtained in the fall months, with 41% of canopy cover. The mid-season K_{cb} when adjusted to the FAO-56 standard climate was 0.43. Seasonal patterns of K_{cb} are presented and the K_{cb} value during the mid-season growth-stage was found to be similar to those described in the literature for Mediterranean climates. Variation of the basal crop coefficient was satisfactorily explained by measured canopy light interception (FIR) and a linear regression model is presented for K_{cb} as a function of FIR.

1. Introduction

Olive trees have been historically cultivated as a dryland crop because of their high resistance to drought. Presently, the use of irrigation for olives has expanded within the intensive arid production areas surrounding the Mediterranean Sea (Gucci and Fereres, 2012). This practice has been spurred by research showing that irrigation increases initial growth rates and ultimately produces higher olive yields than under rain fed conditions (Fernández and Moreno, 1999; Girona et al., 2002a; Moriana et al., 2003). The traditional olive-growing region is the Mediterranean basin, where Spain, Italy and Greece are the main producing countries. Recently, Argentina, Chile and Australia, among other countries, have joined the olive production sector (FAO, 2015). Over the past decade, olive production has steadily increased in Uruguay, due in part to its temperate and sub-humid climate, but also to the availability of land unsuitable for economic production of annual crops. Uruguay has a strategic advantage as an olive producing country because of its proximity and the establishment of trade agreements with large consumer markets like Brazil, the United States, and Canada (ASOLUR, 2015).

Because of the rapid expansion of olive production in Uruguay, research is needed to develop crop management practices for its unique climatic conditions. Uruguay has a mean annual rainfall of 1200 mm, but that rainfall exhibits high inter-annual variability (Castaño et al., 2011), with periods of excess rainfall interspersed with frequent drought periods. Thus, appropriate irrigation management based on actual crop water requirements is a necessity. Most studies on the crop evapotranspiration (ET_c), soil water balance, and irrigation of olive trees were developed in arid and semi-arid climates. Local data of the seasonal variation of ET_c in olive plantations are essential for matching irrigation to meet the volume and frequency of the crop water requirements.

FAO Publication 24 (Doorenbos and Pruitt, 1977) formalized the calculation of crop evapotranspiration as the product of a reference evapotranspiration ET_o and a crop coefficient. This approach has been refined and expanded in subsequent publications (Allen et al., 1998;

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Jensen and Allen, 2016). ET_o was defined as the potential evapotranspiration from a well-water grass surface under standardized field-measurement conditions. Crop coefficients (K_c) are the ratio between measured ET_c and ET_o. The concept was derived under the assumption that weather effects on crop evapotranspiration are mostly explained by the variation in ET_o, while K_c is mostly a function of the type of vegetation and the evolution of the vegetation cover over a crop growing season. This concept has allowed to extrapolate the use crop coefficients developed under particular agroclimatic conditions to other conditions. For example, in the absence of locally developed values, approximate K_c can be derived for local conditions using the algorithms and tables provided by Allen et al. (1998). However, it is well understood that the K_c for crops varies as a function of: a) the fraction of solar radiation intercepted by the canopy (FIR) (Ayars et al., 2003; Girona et al., 2011; Testi et al., 2004; Williams and Ayars, 2005); b) the proportion of wetted soil exposed to evaporation (Allen et al., 1998; Pereira, 2004); and c) stomatal conductance and its relationship with weather variables, such as the vapor pressure deficit (VPD), wind speed, and temperature (Moriana et al., 2002; Villalobos et al., 2000, 2013). These variables are more likely to affect the determination of crop coefficients for orchard crops, mainly because of the differences between tree canopy height and reference grass height and the differences in canopy architecture for different tree species and planting systems.

Many olive researchers have assumed (or proposed) a constant K_c of about 0.55-0.74 to estimate water requirements for irrigated plantations throughout the year in arid and semiarid climates (Goldhamer and Dunai, 1994; Girona et al., 2002a; Grattan et al., 2006). Others, working under arid and semi-arid conditions, have reported a seasonal variation of K_c with low values in summer months and high values in fall and spring months, depending in which season the rains occur (Gucci and Fereres, 2012; Orgaz and Fereres, 2008; Testi et al., 2006). Most of these K_c studies with olive have been carried out in Andalusia (Spain) and California (USA), where summers are hot, dry and vapor pressure deficit can exceed 3.0–3.5 kPa. These conditions are unlike those of Uruguay where the daily mean temperature rarely exceeds 30 °C and the maximum vapor pressure deficit rarely exceeds 2.0 kPa. Villalobos et al. (2013) cautioned against the use of generalized K_c values for fruit trees, irrespective of environmental conditions or crop management practices.

Puppo et al. (2014) conducted an ET_c study with olive trees growing in lysimeters under full irrigation. That study found a linear relationship between the crop coefficient for the summer months and the percentage of canopy cover. While that relationship is valid only for the summer months and the wetting pattern of the drippers used in that study, it can be extrapolated to other conditions by differentiating between the crop transpiration and water losses by soil evaporation, i.e. by using the dual crop coefficient approach (Allen et al., 1998). More precise estimates of ET_c are needed for high frequency irrigation scheduling (Allen et al., 1998; Pereira, 2004), especially in climates with frequent rains and in orchards with different canopy covers in which direct soil evaporation varies significantly (Fereres et al., 2011). Several authors have advocated the use of dual coefficients, with transpiration estimated through the basal crop coefficient, K_{cb}, and direct soil evaporation by the evaporation coefficient, K_e (Wright, 1982; Jensen et al., 1990; Allen et al., 1998; Er-Raki et al., 2010; Fereres et al., 2011). The basal crop coefficient (K_{cb}) is used to estimate evapotranspiration when the soil surface is dry while transpiration is not limited by the soil water deficit (Allen et al., 1998). Various authors indicated that characterizing evapotranspiration for olive trees is inherently difficult because of physiological mechanisms that help to protect the plant from water stress (Connor, 2005; Orgaz and Fereres, 2008). Differences in canopy architecture resulting from different planting arrangements and plant densities, crop management practices, and even plant-to-plant variations, are essential factors which may have a direct effect on K_{cb} (Villalobos et al., 2013; Carr, 2013). Allen and Pereira (2009) proposed a method that adjusts K_{cb} with crop height and canopy cover and ultimately with the density coefficient (K_d which is also influenced by the canopy density (ML) and the stomatal closure (F_r)). Paço et al. (2019) reported successful application of the Allen and Pereira (2009) approach to mature olive orchards.

This study aims to refine the results of Puppo et al. (2014) and improve the resulting ET_c estimates for a wide range of olive orchard production conditions, by removing the soil evaporation component from the total measured crop evapotranspiration and deriving basal crop coefficients for the humid climatic conditions of Uruguay. In addition, the study seeks to verify the seasonal pattern of the K_{cb} in a temperate sub-humid climate and develop a predictive tool for K_{cb} that can be used in practical irrigation management. Two modeling options were explored: 1) by expressing K_{cb} as a function of days past growth initiation (DPGI) and 2) by relating K_{cb} to the midday light interception.

2. Materials and methods

2.1. Location, experiment description, and irrigation

A two-year experiment was conducted at the National Agriculture Research Institute, INIA-Las Brujas Experimental Station (34°40`S, 56°20`W, altitude of 32 m above sea level). Young olive trees (O. europea L.cv. Arbequina) were planted on September 14, 2010, in drainage lysimeters according to the protocol described by Puppo et al. (2014). Several studies have used precision weighing lysimeters to determine water consumption in woody plants, including peach, pear, and apple trees (Ayars et al., 2003; Bryla et al., 2003; Girona et al., 2002b, 2004, 2010; Johnson et al., 2000, 2004). Weighing lysimeters provide highly accurate and reliable daily evapotranspiration data. Drainage lysimeters are less precise but can provide reasonable average data over a time span of 7–15 days, when calculated by water balance and evapotranspiration estimation between two drainage occurrences (Puppo et al., 2014). Several researchers have used drainage lysimeters to determine ET_c in deciduous fruit trees (Boland et al., 1993, 2000; Iancu, 1997; Stevenson, 1989). Recent studies on evapotranspiration of olive trees using lysimeter measurements include Ben-Gal et al., 2010; Agam et al., 2013, 2014; Puppo et al., 2014.

The experimental units consisted of three fiberglass drainage lysimeters 1.9 m long x 0.9 m wide x 1.35 m deep (lysimeters 1, 2, and 3), equipped with 32 mm drain pipes connected to their drainage collection box. The drainage tubes were installed under an 8 to 10 cm gravel layer and covered with a 0.4 mm thick geotextile layer to prevent clogging. Lysimeters (Lys) 1 and 3 were planted with two-year-old trees, and Lys 2 with a four-year-old tree. Data collection for the tree in Lys 2 started on day 122 after planting. This additional time was needed for this older tree to recover from planting stress and completely recover its foliage.

The ET_c of lysimeter-grown trees was measured over two experimental periods, 2010–2011 and 2011–2012 (Puppo et al., 2014). For simplicity, this article will refer to these two periods as years 1 and 2, respectively. Measuring crop evapotranspiration (ET_c) is difficult under high rainfall conditions, as in Uruguay. Hence, the lysimeters were protected with a rain shelter consisting of a rail-mounted steel structure, completely enclosed above and on all sides, with a dual-pitched roof. The shelter was 20 m long, 11 m wide, 8.5 m high along the center, and 6 m high on the perimeter. The shelter was mounted on a rail structure, which allowed the roof to automatically close whenever a logged rain gauge sensor detected more than rainfall 3 mm of rainfall. After rainfall had ceased, the roof was re-opened manually. Because the shelter blocks solar radiation and affects other parameters that influence ET_c, data for days that the shelter was closed, one day before and one after, were excluded from the analysis.

Trees were treated as individual units and were not shaded by neighboring plants (i.e., the incoming solar radiation affected all trees equally). Aerodynamic effects were also considered to equally influence the individual trees (Puppo et al., 2014). In this sense, Allen et al.

(2011) indicated that in humid and sub-humid climates the evapotranspiration process is more heavily influenced by the net radiation availability than by aerodynamic effects. Lysimeters were surrounded by a 30 m by 40 m winter cereal crop alternated with an irrigated summer cereal crop, located in a 446-ha fruit and vegetable orchard. In addition, the experimental conditions simulate the prevailing field environmental conditions of Uruguay's productive olive groves, which have inter-row grass cover. While strong advection effects are unlikely under the conditions of the study, micro-advection effects are possible due to the lower height of the surrounding vegetation.

Each lysimeter was irrigated with three pressure-compensating drip emitters installed in a straight line with a 0.63 m spacing, across the mid-section of the lysimeter. The flow rate was 4 L h^{-1} for each emitter. Irrigation frequency was daily from October to May and once or twice a week from June to September. Irrigation scheduling was determined using the single crop coefficient (K_c) methodology (Allen et al., 1998) applied with local meteorological data to calculate the grass Penman-Monteith ET_o (Allen et al., 1998). Daily climatic data were provided by an automatic meteorological station (Vantage Pro 2, Davis, USA), located at the INIA Las Brujas Experimental Station, 500 m away from the experimental site. The climatic station was installed complying with the installation standards, on a 20 by 20 m grass crop frequently cut, without lack of water, and surrounded by irrigated crops. The same volume of water was applied to each lysimeter each irrigation. Water was applied in excess of the requirements of the young olive trees, to ensure water drainage in the lysimeters. The irrigation amount was determined as 0.7 times the daily ET_o, where 0.7 is the K_c for adult olive trees in high density, as recommended by Allen and Pereira (2009). The drainage system located at the bottom of each lysimeter avoided anaerobic conditions that could occur due to excess water to the trees.

2.2. Soil characteristics

The soil at the experimental station is classified as Typic Argiudoll according to the USDA Classification System and consists of four horizons. Soil textural and water retention parameters were field-determined for each horizon (Casanova, 2008) and are shown in Table 1.

2.3. Determination of crop evapotranspiration (ET_c)

Crop evapotranspiration was calculated over 7- to 14-day periods as the residual of the water volume balance equation:

$$ET_c = R - D \pm \Delta H_s \tag{1}$$

where ET_c is the actual crop evapotranspiration from the olive tree; R is the irrigation volume; D is the drainage volume, and ΔH_s is the change in soil water volume.

Irrigation and drainage water volumes were recorded daily for each lysimeter. Changes in soil water contents were determined with a neutron probe (Campbell Pacific Nuclear Corp., Model 503, CA, USA), using a 1-m long, aluminum access tube placed at the center of each lysimeter, 0.20 m away from the drip emitter line, and halfway between two adjacent emitters. The neutron probe was calibrated gravimetrically for each soil depth, as reported in Puppo et al. (2014), using the

Table 1
Soil texture and classification, bulk density, and water retention parameters for the lysimeter fill soil.

Depth cm	Sand %	Silt	Clay	Textural Classification	Bd[1] g cm^{-3}	FC[2] cm^3	WP[3] cm^{-3}	TAW[4] mm
00–20	24.0	49.3	26.7	Loam	1.28	0.41	0.24	34
20–40	12.2	55.4	32.4	Silty clay loam	1.32	0.38	0.21	32
40–60	12.7	57.5	29.8	Silty clay loam	1.40	0.40	0.23	34
60–90	11.0	74.6	14.4	Silty loam	1.42	0.39	0.22	34

[1]Bulk density. [2]Field capacity. [3]Wilting point. [4]Total available soil water.

methodology described by Haverkamp et al. (1984). Measurements were taken bi-weekly at depths of 0.20, 0.40, 0.60 and 0.80 m.

Following the protocol described previously by Puppo et al. (2014), calculated ET_c did not include data from the periods when a) the amount of available water decreased by more than 50% of the total available water (TAW), b) the amount of available water increased by more than 100% TAW due to blockage of the drainage system in one or more lysimeters, and c) rainy days in conjunction with the days immediately before and after rain event. Rainy days correspond to the days when the lysimeter rain shelter roof automatically closed (see Section 2.1). This data quality control was imposed to eliminate ET_c measurements that could have been affected by anaerobic conditions, and/or reduced photosynthesis induced by shelter closure. Allen et al. (1998) suggest ET_c for olive will be reduced due to water stress after the soil water depletion fraction of the TAW for the root zone reaches 0.65. The lower limit of allowable soil water depletion imposed in our study (50%) helps ensure that the ET_c data measured for trees were obtained under only non-stressed soil water conditions.

The daily calculated volumetric ET_c (i.e., L d^{-1}) was averaged over 7- to 14-day periods and normalized by the area defined by the distances between lysimeter-grown trees (2.5 m x 5.5 m) to derive ET_c in mm d^{-1}. In what follows, this area will be referred to as the tree grid area. This approach was used because the canopy of each tree, and therefore the evaporating area exceeded the area of its lysimeters.

The ET_c was examined as a function of days past growth initiation (DPGI); where DPGI = 1 corresponds to July 11, when olive evapotranspiration rates increase in response to vegetative growth and rising temperatures in the southern hemisphere.

2.4. Determination of K_{cb} and K_e coefficients

Micro-lysimeters were installed within each lysimeter to determine soil evaporation (E_s) (Bonachela et al., 2001; Paço et al., 2006). Determination of soil evaporation allows calculation of the basal (transpiration) portion of ET_c by subtracting E_s from the measured ET_c. The micro-lysimeters consisted of PVC tubing, 0.084 m inner diameter and 0.12 m long, as described by Bonachela et al. (2001). With these dimensions, 1 mm of evaporated water produces a 5.5 g weight difference. The devices were buried flush with the ground surface, removed, and capped at their bottom. The micro-lysimeters were weighed over 7 consecutive days, which is the maximum irrigation interval in this study.

The micro-lysimeter measurements were conducted over two summer periods in 2013. In the first period (DPGI 217 to DPGI 223), two micro-lysimeters were installed in the exposed-wetted fraction, two in the shaded-wetted fraction, two at the dry edge of the wetted fraction, and two at the exposed-dry fraction. In the second period (DPGI 230 to DPGI 236), since the measured evaporation was found to be negligible in the dry and dry edge of the wetted fraction, a second 7-day analysis was performed in which four micro-lysimeters were placed in the exposed-wetted fraction and four in the shaded-wetted fraction. The applied volume was 48 L and 36 L a day, for the first and the second period respectively; the resulting wetting fraction was 3–6% of the grid area. The amount of water applied at each irrigation (ET_ox0.7) was enough to fully fill the surface soil layer to field capacity and to drain excess, such that the depletion of the layer was returned to the same amount of water of the previous day in each instance. Thus, the amount of water in the layer at the start of each drying cycle was the same with each irrigation.

The evolution of the soil evaporation coefficient (K_e) with time was examined for both the exposed-wetted fraction and the shaded wetted fraction.

A mean K_e value was used for the period between two consecutive irrigations, based on the micro-lysimeter results.

The soil evaporation coefficient was normalized by the tree grid area taking into account the number of days between irrigations, from the K_e vs time function, and was then calculated as follows:

$$K_e = K_{e,e} \times f_{ew} + K_{e,s} \times f_w \quad (2)$$

In Eq. (2), f_{ew} is the exposed-wetted soil fraction of the tree grid area, which is the surface that accounts for most of the evaporation (Allen et al., 1998) ; f_w is the shaded-wetted soil fraction of the tree grid area; $K_{e,e}$ is the corresponding value of the evaporation coefficient throughout the period in-between irrigations for the exposed-wetted fraction and $K_{e,s}$ is the corresponding value of the evaporation coefficient for the interval between irrigations for the shaded-wetted fraction.

The normalized soil evaporation (E_s) was calculated as

$$E_s = K_e \times ET_o \quad (3)$$

This result was then used to calculate the normalized K_{cb} coefficient:

$$K_{cb} = (ET_c - E_s)/ET_o \quad (4)$$

where ET_c and E_s are measured crop evapotranspiration for the olive trees and direct soil evaporation, respectively, as normalized for the tree grid area and ET_o is the FAO-PM reference evapotranspiration, where units for all are expressed in mm d^{-1}.

Monthly mean K_{cb} values were determined for year 1 and year 2. The seasonal pattern of K_{cb} were determined for both years as a function of DPGI. A K_{cb} FAO-56-style model was developed from data of year 2 only and is described further in Section 2.6. A similar model was not developed for year 1 because the ET_c was measured starting on planting date (DPGI 66), and data were not collected for Lys 2 until DPGI 188 due the time needed for this tree to recover transplant stress. Furthermore, trees sizes for the lysimeters, including height and canopy cover, were very different until early in the second year.

2.5. Measurement of vegetative growth and midday canopy light interception

Canopy size measurements are needed to interpret the evapotranspiration measurements and adjust the evaporation coefficient estimates with time. The longitudinal and transverse diameters and the height of the canopy of each tree were measured every three months. The area of the canopy was calculated assuming a circular shape from the mean diameter, and the canopy cover was calculated as the ratio between the area of the canopy (m^2) and the tree grid area (2.5 m x 5.5 m). The trees were pruned at the same time on DPGI 360 (July 5, 2012), at the end of the second year, and each tree was fertilized in the spring with 200 g of 46-0-0 (N-P-K).

One of the goals of this study is to examine the relationship between K_{cb} and a measure of crop canopy coverage. To this end, the fraction of canopy light interception (FIR) was selected. FIR is defined as (Girona et al., 2011):

$$FIR = 1 - \frac{mean\ PAR\ value\ at\ ground\ level}{PAR\ value\ above\ canopy} \quad (5)$$

In this expression, PAR is the canopy light interception of photosynthetically active radiation. Several authors have estimated the K_c of fruit trees and olives as a function of either FIR or canopy coverage (Ayars et al., 2003; Girona et al., 2010; Testi et al., 2004; Williams and Ayars, 2005). Since olive trees have a lower density of leaves than other species of fruit trees such as apples and pears (Allen and Pereira, 2009), and since the olive pruning has the main objective to favor the entry of light through the canopy for which some branches are removed (García-Ortiz et al., 2008) the use of FIR seems reasonable in comparison with the canopy cover which takes into account the size of canopy only. PAR was measured at solar noon ± 60 min on clear days with a ceptometer (Decagon Devices Inc., model LP-801, WA, USA, probe length = 86.5 cm). 30 readings were obtained for each lysimeter, at pre-defined locations covering the tree grid area, as described by Girona et al. (2011). The ceptometer was located at ground level and in a horizontal position. The above-canopy PAR was measured by taking a reading with the ceptometer in an open place.

To ensure that ceptometer measurements correspond to solar noon, they need to be corrected by the solar angle with respect to the zenith, as detailed in the operator's manual. (Decagon Devices, Inc., 2010).

2.6. Development of relationship for K_{cb} as a function of DPGI and FIR

A commonly used approach for modeling K_c or K_{cb} is as a function of the growing season duration. The variation of K_{cb} with DPGI was fitted to a four-segment linear model, as suggested by FAO-56 (Allen et al., 1998; Hunsaker et al., 2002, 2007). In this approach, K_{cb} is assumed as a constant during the first time interval (K_{cb1}). This is followed by a period of increasing K_{cb} up to a constant value (K_{cb2}), which is maintained for another period of time (K_{cb3}), after which it decreased to (K_{cb4}). The parameters were estimated using least squares and solved with the Excel Solver tool, as suggested by Wraith and Or (1998).

for DPGI < $DPGI_{t1}$; K_{cb1} = constant (6)

for $DPGI_{t1}$ < DPGI < = $DPGI_{t2}$; K_{cb2} = (DPGI - $DPGI_{t1}$) * b_1 + constant;

for $DPGI_{t2}$ < DPGI < = $DPGI_{t3}$; K_{cb3} = b_1 * ($DPGI_{t3}$ - $DPGI_{t2}$) + constant;

for $DPGI_{t3}$ < DPGI; K_{cb4} = b_1* ($DPGI_{t3}$ – $DPGI_{t2}$) + b_2 * (DPGI - $DPGI_{t3}$) + constant;

where $DPGI_{t1}$, $DPGI_{t2}$ y $DPGI_{t3}$, are the ending days for initial stage ($_{t1}$), crop development stage ($_{t2}$) and mid-season stage ($_{t3}$), respectively. The coefficients b1 and b2 are the regression coefficients for the crop development and final stages, respectively.

As mentioned previously, since the first-year ET_c measurements were limited and plant size was very heterogeneous, the K_{cb}-DPGI relationship was solely modeled using data from the second year.

To evaluate the evolution of FIR through time, the FIR data were fitted as a function of DPGI. The FIR measurements from the two years were combined and used to calibrate K_{cb} as a function of FIR using linear regression. Unlike the four-segment K_{cb} model, the FIR model does not require a complete yearly set of K_{cb} data (i.e. year 1) and is not time-driven. For the model-fitting and validation a set of 46 observations (adjustment set) were chosen between the two years and the three lysimeters. Then validation was conducted with 15 randomly chosen observations which were not used in the linear regression calibration model. The statistical distribution of the residuals was analyzed with the modified Shapiro-Wilks test, to verify the absence of bias and the normality of the residuals.

The measured K_{cb} values were also adjusted as a function of canopy cover to allow a clearer comparison of our data with other reported values. The adjustment was made using the relationship developed for almonds by Fereres et al. (1981), which has also been verified to apply to olive orchards (Fereres et al., 2011):

$$K_r = -0.0194 \times CC^2 + 2.8119 \times CC - 1.008 \quad (7)$$

Here K_r is the reduction coefficient and CC is the canopy cover. This reduction coefficient can be used to determine the K_{cb} at 100% canopy cover given the K_{cb} value measured at a particular CC, for example K_{cb} (at 25%) = K_{cb} (100%) x Kr/100.

Allen and Pereira (2009) proposed a procedure for estimating $K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$ values of various crops, including orchards, from effective fraction of ground cover measurements and canopy height. Thus, it seems useful to compare the $K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$ values generated in this study with values computed with the Allen and Pereira (2009) procedure, based on the average ground cover and average canopy height measurements of the three trees of our study. The ML and the mean leaf resistance values, suggested by Allen and Pereira (2009) for olive trees, was used.

The software InfoStat / P (Di Rienzo et al., 2014) was used to

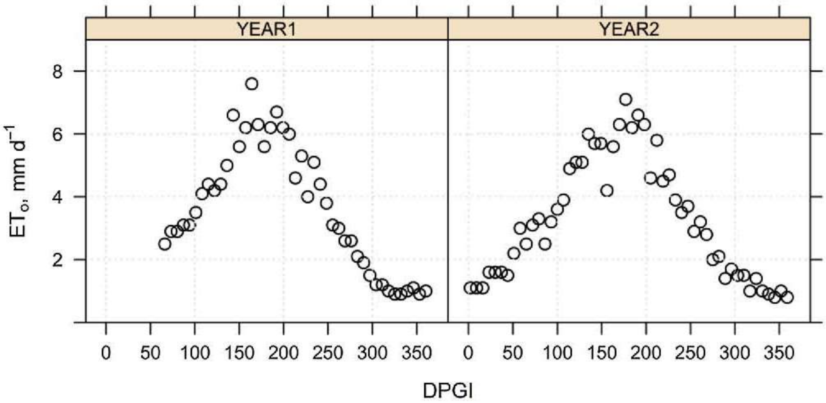

Fig. 1. Seasonal variation of weekly mean values of ET_o FAO-PM for year 1 and year 2. Horizontal axis: days past growth initiation (DPGI), where DPGI 1 corresponds to July 11 in both years.

develop the linear regression of the K_{cb}-FIR model and to develop the four-segment K_{cb}-DPGI model. The models were considered satisfactory when the p-value was < 0.05. The distribution of residuals errors was analyzed using the Shapiro-Wilk test provided as an option in the software. Residuals distribution was considered normal when the Shapiro-Wilk p-value was < 0.05.

3. Results and discussion

3.1. Environment conditions

In Figs. 1 and 2 displays the weekly average ET_o and the weekly average VPD, R_s and T_a data for year 1 and year 2, respectively. ET_o and the measured weather variables exhibited similar patterns of variation as a function of DPGI and peak values during the two years of the study. During year 1, peak ET_o FAO-PM values were recorded in the last week of December (DPGI 164–171), with a weekly mean of 7.6 mm d^{-1} and daily values in that week ranging from 6.6 to 8.4 mm d^{-1}. During year 2, the weekly mean ET_o peaked at 7.1 mm d^{-1} during the first week of January (DPGI 177–184), with daily values varying between 5.6 and 9.1 mm d^{-1}. Comparison of data in Figs. 1 and 2 clearly suggest a strong correlation between ET_o and any of the measured weather variables.

The measurements confirm that high humidity and low temperature conditions prevail in Uruguay, and thus the ET_o is relatively low. The highest weekly average VPD was 2.3 kPa in year 1, while all values were below 2.0 kPa in year 2. These values are lower than those reported by Villalobos et al. (2013), in the range of 2.7–3.3 kPa, for eight experiments conducted in different locations in Spain and California. The maximum values of the average weekly temperature were 26.1 and 23.4 for year 1 and year 2, respectively. In contrast, Grattan et al. (2006) indicated that the summer temperature of California often exceeds 35 °C. Testi et al. (2004) reported peak monthly ET_o values of 6.6 to 7.1 mm d^{-1} for southern Spain while Grattan et al. (2006) reported values from 6.6 to 6.8 mm d^{-1} for California. The peak monthly mean ET_o measured in this study were about 5–15% lower, 6.5 and 6.1 mm d^{-1} for December and January (2010–2011) and 5.5 and 6.2 mm d^{-1} for December and January (2011–2012) respectively.

Mean weekly ET_o values were also calculated from climatic data collected for the years 1997–2018 in the same area where the experiment was undertaken (data not shown). Evaluation showed that the total yearly ET_o measured in years 1 and 2 of our experiment exceeded the total ET_o determined in all other years in this time series except for

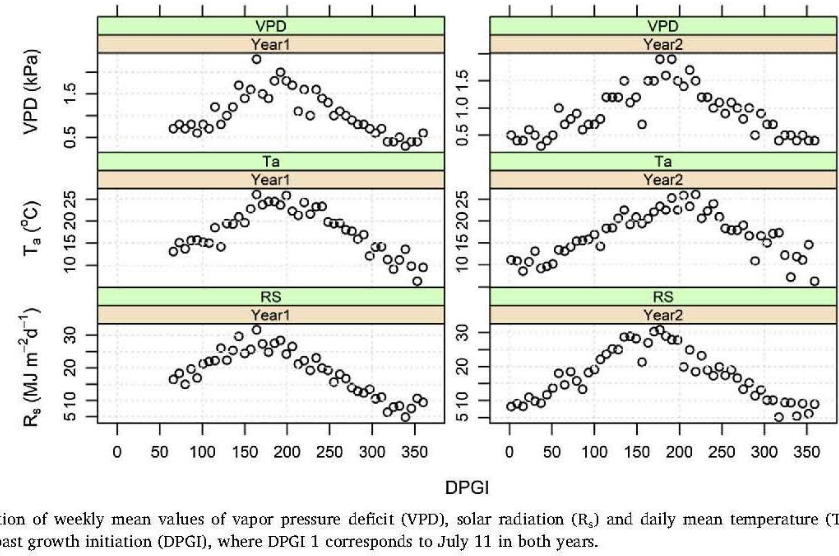

Fig. 2. Seasonal variation of weekly mean values of vapor pressure deficit (VPD), solar radiation (R_s) and daily mean temperature (T_a) for year 1and year 2. Horizontal axis: days past growth initiation (DPGI), where DPGI 1 corresponds to July 11 in both years.

Table 2
Evaporation measured with micro-lysimeters installed in four fractions of the lysimeters.

Evaporation (mm d^{-1}) at the exposed-wetted fraction					ET_o (mm d^{-1})			
Days after irrigation	1	2	3	7	1	2	3	7
Micro-lysimeters								
1a	4.9	1.6	0.9	1.1	5.6	3.6	4.7	5.3
2a	3.6	2.0	0.9	–	5.6	3.6	4.7	5.3
1b	4.7	4.2	0.9	0.8	5.7	4.6	4.0	3.8
2b	4.9	2.2	0.7	1.1	5.7	4.6	4.0	3.8
3b	4.2	2.2	0.5	1.0	5.7	4.6	4.0	3.8
Mean value	4.5	2.4	0.8	1.0	5.7	4.2	4.3	4.4
Evaporation (mm d^{-1}) at the shaded-wetted fraction					ET_o (mm d^{-1})			
Micro-lysimeters								
3a	2.2	0.9	0.9	1.1	5.6	3.6	4.7	5.8
4a	2.2	0.9	1.6	1.3	5.6	3.6	4.7	5.8
5b	4.2	1.8	0.7	0.9	5.7	4.6	4.0	4.2
6b	4.2	0.9	0.0	1.0	5.7	4.6	4.0	4.2
Mean value	3.2	1.1	0.8	1.1	5.7	4.1	4.4	5.0
Evaporation (mm d^{-1}) at the exposed-dry fraction					ET_o (mm d^{-1})			
Micro-lysimeters								
5a	0.0	0.0	0.2	0.1	5.6	3.6	4.7	5.3
6a	0.2	0.2	0.0	0.2	5.6	3.6	4.7	5.3
Mean value	0.1	0.1	0.1	0.1	5.6	3.6	4.7	5.3
Evaporation (mm d^{-1}) at the dry edge of the wetted-fraction					ET_o (mm d^{-1})			
Micro-lysimeters								
7a	0.4	0.4	0.4	0.4	5.6	3.6	4.7	5.3
8a	0.5	0.4	0.4	0.2	5.6	3.6	4.7	5.3
Mean value	0.5	0.4	0.4	0.3	5.6	3.6	4.7	5.3

a: Micro-lysimeters used in the first test; b: Micro-lysimeters used in the second test.

one year. Hence, the two experimental years can be characterized as years that experienced high atmospheric crop water demand for southern Uruguay.

3.2. Evaporation coefficient (K_e)

The wetted area due to irrigation and measured in each lysimeter, which remained almost constant, because the amount of irrigation water was always in excess with respect to the water requirement of the plants, but proportional to the atmospheric demand (ET_o). The area of the wetted spot ranged between 0.37 and 0.86 m^2, where the largest value corresponded to Lys 3 that had a smaller tree than the other lysimeters. The proportion of f_{ew} and f_w was updated every 3 months when the size of the plants was recorded. The shaded-wetted soil fraction (f_w) was 1.0 from the beginning of the experiment for the Lys 1 and Lys 2, while f_w varied between 0.88 and 1.0 in Lys 3, reaching the value 1.0 at the beginning of the second year.

Table 2 shows the direct soil evaporation (E_s) values measured with the micro-lysimeters as well as ET_o as a function of days past irrigation and are grouped by measurement type (i.e., exposed-wetted fraction). As expected, evaporation was negligible in the dry area and at the dry edge of the wetted fraction (Table 2), as previously found in evaporation studies for drip-irrigated olives by Bonachela et al. (2001). It is clear that these surrounding dry areas within the lysimeter do not need to be considered for the calculation of K_{cb}. Evaporation was greatest for exposed-wetted fraction, as expected. One day past irrigation, measured E_s values for the exposed wetted fraction were about 20% less than the ET_o for that day. This reflects a significant amount of initial evaporation from the exposed emitter areas. However, daily E_s diminished quickly relative to ET_o thereafter. Starting at three days after the irrigation and until the end of the measurement period, the evaporation rate from micro-lysimeters in the shaded wetted fraction was close to the evaporation rate from micro-lysimeters in the exposed wetted fraction (Table 2).

Fig. 3 presents the resulting evaporation coefficients computed for the drying cycle after irrigation.

The available energy is, together with the amount of water, the main driver of the evaporation process, hence it makes sense that the initial values of the K_e and the rate of decrease were higher in the exposed-wetted fraction than the shaded-wetted fraction. At the end of the 7-day drying cycle, the K_e mean values were very similar 0.22 and 0.21 for the exposed and shaded wetted fraction respectively. The equations representing the solid lines in Fig. 3 are:

$$\text{(a)} \quad K_{e,e} = 0.7516 \times Days^{-1.008}; \quad R^2 = 0.72 \tag{8}$$

$$\text{(b)} \quad K_{e,s} = 0.6018 \times Days^{-0.64}; \quad R^2 = 0.70 \tag{9}$$

The determination of E_s by the micro-lysimeter data could slightly overestimate the evaporation (Klocke et al., 1990). If this were the case, we could be slightly underestimating the tree transpiration and the resulting adjusted K_{cb} coefficients. However, the wetted soil fraction in our study, from which direct evaporation would be produced, was very small in relation to the tree grid area. Thus, any overestimation of actual E_s had a small consequence on our transpiration estimates.

3.3. Canopy cover, soil water content, and crop evapotranspiration measurements

Canopy cover measurements for each year and lysimeter are shown in Fig. 4. The tree in Lys 2 was 4 years old when transplanted while the other two plants were 2 years old. This explains the differences in canopy size, especially in year 1. In the second year, tree canopies became more alike as the season progressed. In year 1, tree canopy size measurements started on DPGI 177, while ET_c measurements started on DPGI 188, when the four-year old tree had fully recovered its foliage density. Plant diameter and height measurements, which are not

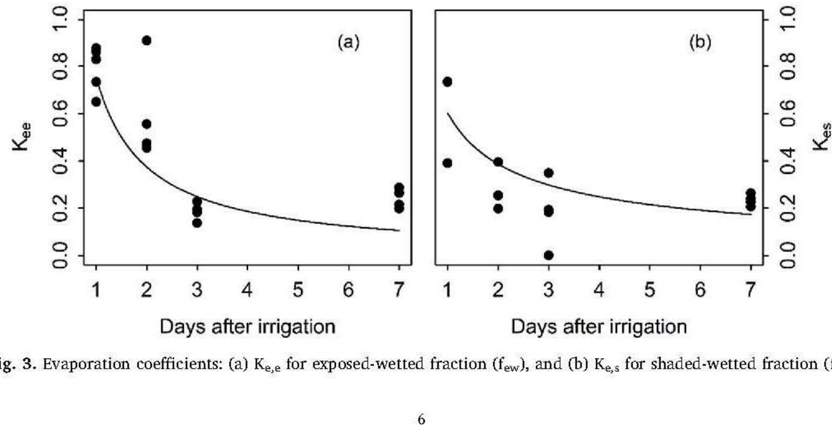

Fig. 3. Evaporation coefficients: (a) $K_{e,e}$ for exposed-wetted fraction (f_{ew}), and (b) $K_{e,s}$ for shaded-wetted fraction (f_w).

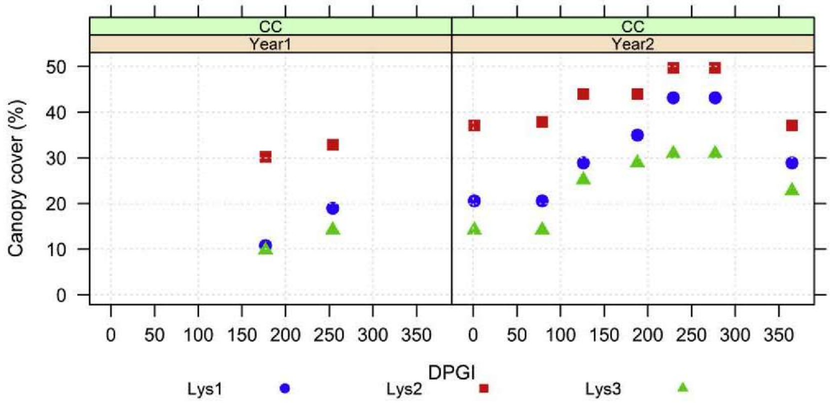

Fig. 4. Canopy cover (area canopy*100/tree grid spacing [5.5 × 2.5] m^2) for different DPGI during the periods 2010-11 and 2011–2012. Horizontal axis: days past growth initiation (DPGI), where DPGI 1 corresponds to July 11 in both years.

shown, followed the same trends in time as the canopy measurements, and also produced larger values for the tree in lysimeter 2.

Fig. 5 presents the volumetric soil water content measured with the neutron probes and averaged for the first 60 cm of the soil profile. This is the depth where roots were concentrated. In this soil the wilting point was 23% and the saturated soil was 50%. Some periods of water deficit or excess were experienced during year 1 and those data were discarded from the analysis. The figure shows that during the second year the water content was maintained at 50% or above for all but a few instances for Lys 1, in which depletions was slightly above 50% depletion. Occasionally, measured soil water content slightly exceeded field capacity for Lys 3. In particular, depletion was above 50% during the period of highest ET_c demand in year 2 for all three lysimeters. As 65% depletion is considered the critical level for olive water stress (Allen et al., 1998) we submit that ET_c measurements presented below were obtained under well-watered conditions. Overall, these results suggest that the number of emitters used and their location within the lysimeters did not affect the availability of water to the plants. As was previously indicated, the applied volume for each irrigation was expected to fully satisfy the crop water demand.

ET_c was measured starting on the planting date (DPGI 66) in year 1, except in Lys 2 which began on DPGI 188. In year 2, measurements were obtained throughout the entire year.

Fig. 6 shows the mean daily crop evapotranspiration values measured for each month and lysimeter. Note that ET_c peaked in January in both years (DPGI 175–205), when ET_o (Fig. 1) also attained maximum values. Larger ET_c values were measured during the second year of the study, in response to higher trees and, therefore, canopy growth than in year 1. The relatively small values of ET_c in comparison with ET_o (Fig. 1) are a consequence of the relatively small canopy in relationship to the grid area. Despite the difference in tree size, similar ET_c values were measured for all trees during most months. The tree in lysimeter 3 produced the smallest ET_c values during the development period, consistent with the fact that it was also the tree with the smallest canopy.

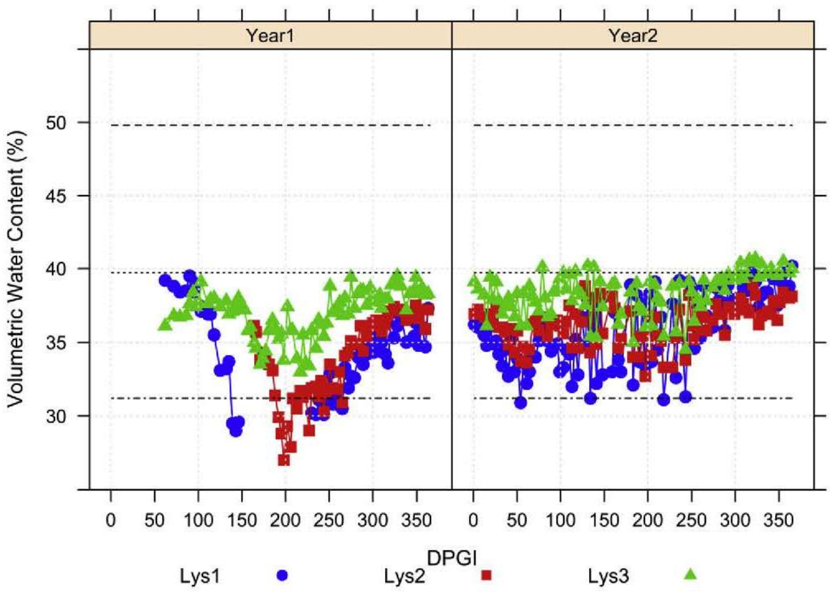

Fig. 5. Average volumetric water contents from 0 to 60 cm, as a function of DPGI for the three lysimeters. The upper dashed line represents saturation, the middle line is field capacity, and the lower line is 50% soil water depletion. Horizontal axis: days past growth initiation (DPGI), where DPGI 1 corresponds to July 11 in both years.

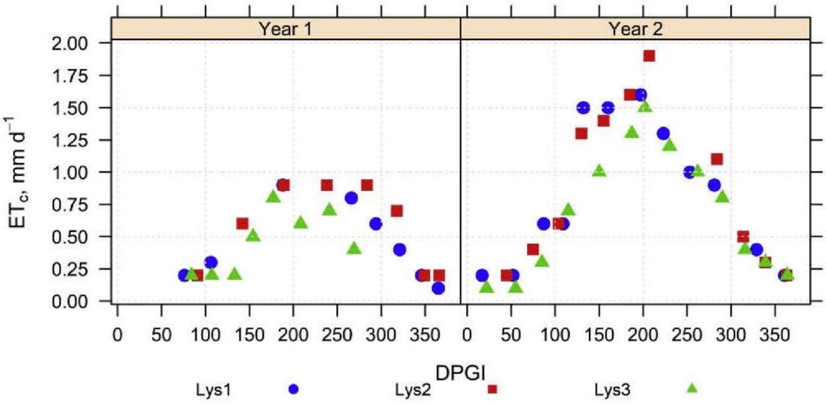

Fig. 6. Mean monthly crop evapotranspiration (ET_c) of the lysimeter-grown trees for year 1 and year 2. Horizontal axis: days past growth initiation (DPGI), where DPGI 1 corresponds to July 11.

3.4. Basal crop coefficient (K_{cb})

Fig. 7 presents the resulting K_{cb} and K_e coefficients. Peak K_{cb} values were recorded between DPGI 280 and DPGI 321 (fall) both years, while minimum K_{cb} values were recorded in late winter and early spring of the second year, which spanned the full annual cycle of the olive trees. This seasonal pattern of K_{cb} agrees with the pattern reported by Gucci and Fereres (2012), who indicated that the relative transpiration (described by K_{cb}) of olive trees shows a marked annual variation, with minimum values in spring and maximum values in early fall. The difference between the periods corresponding to the maximum ET_o values (Fig. 1) and the maximum K_{cb} values (Figs. 7 and 8) determined low values of ET_c, respect to ET_o values.

In year 1, the computed K_{cb} values differed substantially among trees. These differences, however, do not appear to be related to tree canopy size, as Lys 1 produced larger K_{cb} values than Lys 2. In year 2, the K_{cb} values for the three trees were in better agreement with each other and results were related to tree canopy cover, with peak K_{cb}

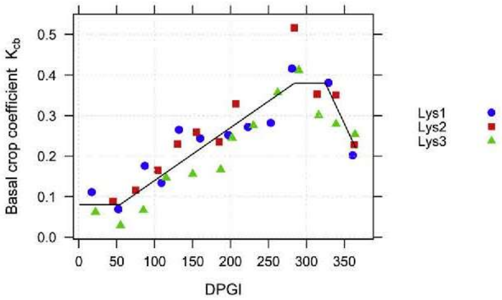

Fig. 8. Variation of the K_{cb} as a function of DPGI combining K_{cb} data for three trees. $K_{cb\ ini} = 0.08$; $K_{cb\ mid} = 0.38$ and $K_{cb\ end} = 0.22$. Horizontal axis: days past growth initiation (DPGI), where DPGI 1 corresponds to July 11.

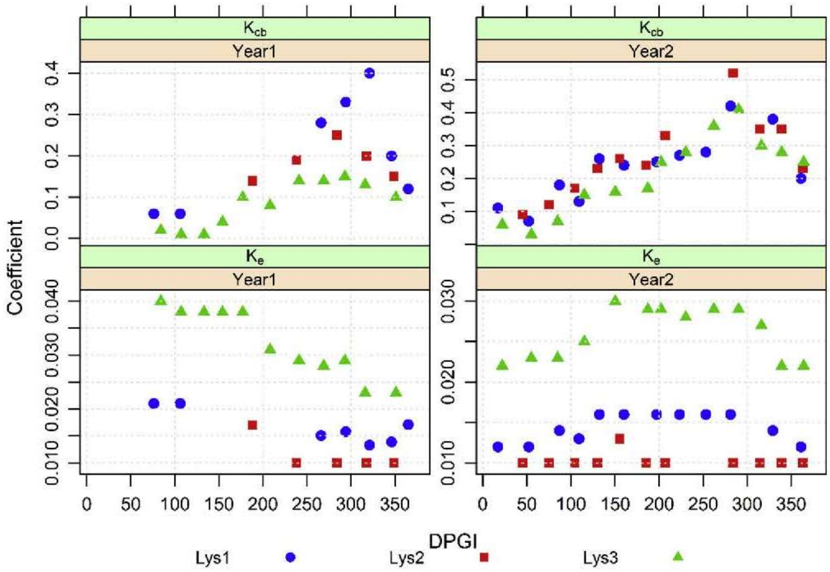

Fig. 7. Mean monthly K_{cb} and K_e measured with three olive trees grown in lysimeters for the two experimental years. Horizontal axis: days past growth initiation (DPGI), where DPGI 1 corresponds to July 11.

values varying between 0.37 and 0.52 (Fig. 7). These maximum K_{cb} values are like to those reported by Villalobos et al. (2000) in the Mediterranean (0.44 to 0.48), for olive trees with 40% canopy cover; and to the value recommended by Allen and Pereira (2009), 0.55, for a canopy cover of 50%.

The K_e values did not exhibit the same strong seasonality as K_{cb} (Fig. 7). Note also that the K_e values determined in this analysis were an order of magnitude smaller than the K_{cb} values and that larger K_e values were determined for the tree with the smallest canopy. E_s was small in comparison with ET_c because the wetted section was small relative to the tree grid area. Hence, despite high K_e values measured in the wetted section (Fig. 2), K_e mean monthly values normalized for the tree grid were small (Fig. 7) and nearly constant both years, between 0.01 and 0.03 (Fig. 7).

Although the K_{cb} data shows some scatter due to tree size variation, the olive K_{cb} data for year 2 were described satisfactorily with the FAO-56 segmented crop coefficient model (after Allen et al., 1998), as shown in Fig. 8. The calculations produced an R^2 of 0.83 and a mean squared error (MSE) of 0.0021. Also, as shown in Fig. 8, the scatter of measured K_{cb} data about the predicted curve (or residuals) are fairly uniform for all three trees, despite the age difference for the Lys 2 tree.

The trees had low initial K_{cb} values up to DPGI = 54, after which K_{cb} increased linearly up to DPGI = 284 (crop development stage), at the rate given by the regression coefficient b1 = 0.0013 day^{-1}. The K_{cb} remained fairly constant up to DPGI = 325 (mid-season stage), and then declined sharply during DPGI from 325 to 365, at a rate given by the regression coefficient b2= -0.004 day^{-1}. The trees also reached their maximum size approximately at the mid-season stage, with a mean ground cover of 41% (Fig. 4). However, the mid-season stage was short (30 days) compared to the length (60 days or more) of this stage reported for some annual crops (Hunsaker et al., 2007; Yang et al., 2016) and for deciduous fruit trees (Snyder et al., 2000; Ayars et al., 2003). Other authors have suggested that the K_{cb} value, of perennial trees and particularly olive trees, is controlled by stomatal conductance (Villalobos et al., 2000; Moriana et al., 2002) than by increasing foliar area (Fereres et al., 2011). This may be a factor contributing to the short duration of the mid-season K_{cb} stage.

The K_{cb} values measured in this study are comparable to values measured in other studies. López-Olivari et al. (2016) conducted a two-year evapotranspiration study with olives planted at very high density in the Maule region, in Chile. That study site is located at nearly the same latitude as this study but with semiarid climate conditions. Those authors reported maximum $K_{cb\ mid}$ values of 0.28 and 0.31 for canopy cover of 29 and 31% respectively.

Working also with drip-irrigated olives, Testi et al. (2004) reported a K_c of 0.30 for periods without rain and when the soil surface was dry. Under these conditions, the coefficient reported by these authors can be regarded as equivalent to K_{cb}. However, those results were measured when canopy cover was only 25%. Hence, to compare the K_{cb} values measured in this study with those of Testi et al. (2004), the K_{cb} data were adjusted considering canopy cover and using Eq. (7). According to this adjustment, the K_{cb} for our trees at 100% canopy cover would be 0.46, which is close to the K_{cb} value of Testi et al. (2004), 0.52, when adjusted at 100% canopy cover. It should be noted that comparisons between our results and those of previous studies are based on non-standardized K_{cb} values, as those reports did not use the FAO-56 standardization procedure.

Using our average measured weather data and crop heights (shown in Table 3), our observed K_{cb} values for mid-season and end-of-season were adjusted to the standard climatic conditions of FAO-56, i.e., RH_{min} = 45% and u_2 = 2 m/s. The resulting values are $K_{cb\ mid\ (Std)}$ = 0.43 and $K_{cb\ end\ (Std)}$ = 0.27. These are smaller than the tabulated K_{cb} values presented in FAO-56 (0.55, 0.65, 0.65, respectively) for olives trees. The standardized values in FAO-56 were observed for more mature trees having canopy cover 40–60%.

Table 3
Parameters used to estimate $K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$ from effective ground cover and height, according to Allen and Pereira (2009).

	Initial	Mid-season	End late-season
Factor of canopy density (ML)	1.5	1.5	1.5
Height tree (h) (m)	2.4	2.9	2.6
Mean leaf resistance (r_1) (s m^{-1})	950	950	1000
Slope saturation vapour pressure vs. air T curve (Δ) (kPa °C^{-1})	0.084	0.11	0.071
Psychrometric constant (γ) (kPa °C^{-1})	0.67	0.67	0.67
Canopy cover (%)	24	41	30
Effective fraction of ground covered (fc_{eff})	0.38	0.68	0.54
Stomatal closure (Fr) (s m^{-1})[a]	0.32	0.43	0.35
$K_{c\ min}$ for bare soil in agricultural	0.15	0.15	0.15
$K_{cb\ full}$	0.37	0.49	0.40
Minimum relative humidity (RH_{min}) (%)	54.08	52.39	53.80
Wind speed (u_2) (m s^{-1})	2.25	1.43	1.60
Mean temperature (°C)	10.39	15.06	7.55
Density coefficient (K_d)[b]	0.57	0.90	0.81
K_{cb}	0.28	0.45	0.35

[a] $Fr \approx \frac{\Delta + \gamma(1 + 0.34u_2)}{\Delta + \gamma\left(1 + 0.34u_2 \frac{r_l}{100}\right)}$.

3.5. *Estimating basal crop coefficient from effective fraction of ground cover and height*

Results of K_{cb} derived from ground cover and canopy height measurements (Allen and Pereira, 2009) are shown in Table 3. The predicted $K_{cb\ ini}$, $K_{cb\ mid}$, and $K_{cb\ end}$ were larger than our FAO-56 K_{cb} values derived from measurements, especially K_{cb} for the initial stage, which was only 0.08. However, these differences in K_{cb} seems reasonable given the relatively young trees and the humid conditions of this experiment under which ET_c was measured. Also, differences in K_{cb} could be due to the estimation of the stomatal closure factor (Fr) with the equation suggested by Allen et al. (1998), into account the mean leaf resistance (rl), the slope saturation vapor pressure vs. air T curve (Δ) and psychrometric constant (γ). The results of Table 3 were calculated with published values of stomatal conductance. Working with data from a super-high plant density olive orchard, in a dry sub-humid climate, Paço et al. (2019) calibrated the values of Fr through comparing the Allen and Pereira (2009) K_{cb} values with the Kcb calculated from Dual K_c approach.

3.6. *Relationship between fraction of canopy light interception (FIR) and K_{cb}*

Fig. 9 presents the FIR measurements as a function of DPGI. As expected, FIR values exhibited seasonal patterns that are somewhat related to the canopy cover measurements illustrated in Fig. 4. Note however that FIR and canopy measurements differed substantially among trees. In year 1, the tree with the largest canopy, in Lys 2, obtained relatively small changes in FIR values after DPGI 200 while the tree with the smallest canopy, in Lys 3, exhibited the largest change in FIR during the year and, ultimately, the largest FIR values at about DPGI 300 in year 1. In year 2, FIR for the tree in Lys 1 was higher than others starting around DPGI 150 and continuing to DPGI 280. Thus, during summer in year 2, Lys 1 had higher FIR but lower canopy cover than Lys 2 (Fig. 4). As was noted earlier, the measured ET_c was similar among plants in the second year despite differences in canopy cover. Altogether, these FIR results suggest that leaf density was very different among the trees and that canopy cover may provide an incomplete measure of canopy contribution to evapotranspiration. Therefore, examining K_{cb} as a function of FIR can be justified. Fig. 10 shows K_{cb} as a function of FIR. The scatter in the data appears to increase with increasing FIR. Nevertheless, the results do suggest there is linear

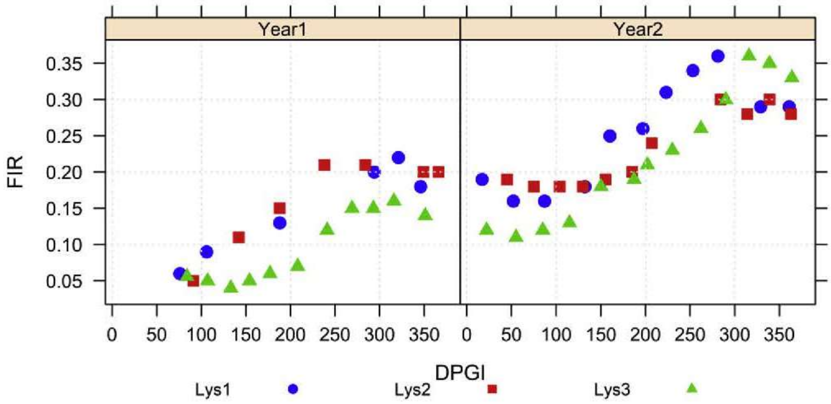

Fig. 9. Variation of the fraction canopy light interception (FIR) as a function of DPGI. Horizontal axis: days past growth initiation (DPGI), where DPGI 1 corresponds to July 11.

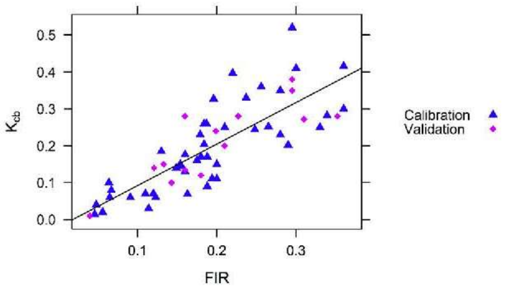

Fig. 10. Variation of the K_{cb} as a function of fraction canopy light interception. The triangles represent the data used to fit a linear relationship between the variables, the diamonds the data used to evaluate the goodness of fit.

relationship between K_{cb} and FIR. The regression equation is represented by the solid line in Fig. 10 (R^2 = 0.66, n = 46).

$$K_{cb} = -0.0317 + 1.2081 \times FIR \tag{10}$$

According to this model, FIR explained 66% of the variation in K_{cb}. For the validation set, the computed R^2 was 64% (regression line not shown).

The residuals of both the regression and validation K_{cb} vs FIR data sets were examined and found to be normally distributed. For the validation data set, estimation errors varied from -0.117 and 0.118 K_{cb} (Fig. 11). The mean error of the estimated K_{cb} as a function of FIR values was 0.008, and the 95% of these errors were less than 0.115.

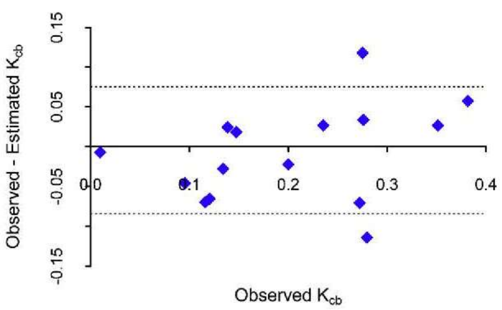

Fig. 11. Validation error values of modeled K_{cb} as a function of FIR with respect to the observed K_{cb}. The segmented lines represent the percentiles 5 and 95 of the errors.

Previous studies have examined the relationship between K_{cb} and FIR for other perennial crops. Ayars et al. (2003) evaluated this relationship for peach trees in California and found, using a 5-year data set. They obtained a strong linear relationship between K_c and FIR (R^2 = 0.86). The relationship was improved (R^2 = 0.93) when the component of direct soil evaporation was eliminated from the K_c coefficient. Girona et al. (2011) evaluated FIR in apple and pear orchards. In contrast with Ayars et al. (2003), these authors determined an exponential relationship between K_c and FIR for apples (R^2 = 0.91), but did not develop a relationship for pears due to the wide scatter of the data. Girona et al. (2011) attributed these contrary results to differences between species in canopy porosity and stomatal sensitivity to VPD. In an experiment with young olive trees in southern Spain, Testi et al. (2004) fitted a linear regression between K_c in dry soil conditions (essentially K_{cb}) and canopy cover, which is related to FIR.

Consideration of the contrasting results obtained in previous studies and the limitations of this study, particularly that measurements were obtained for less than two full years, our findings suggest that FIR can potentially serve as a tool for estimating K_{cb}, but that the proposed relationship cannot be used in practice without additional measurements. On the other hand, it is important to note that while the relationship of K_{cb} as a function of DPGI could vary between years, in response to different durations of the growth stages, management practices, etc., the relationship of K_{cb} as a function of FIR could potentially be valid from year-to-year.

3.7. Accuracy estimates

The K_{cb} relationships developed in this study were evaluated by comparing the observed with the estimated transpiration. The observed transpiration (T) were calculated as the averaged of the T measurements for each stage growth and for each lysimeter. The estimated transpiration were calculated as $T_e = K_{cb} \times ET_o$, where ET_o was determined as the mean value for each growth stage. The K_{cb} estimates were presented as a function of DPGI (method 1), as a function of FIR (method 2) and with the procedure of Allen and Pereira (2009) (method 3). In method 1, K_{cb} estimates were developed by accounting for the duration of the growth stages according to Fig. 8, and then a mean value was calculated for each stage. The coefficients used in the method 3 are those of Table 3; the K_{cb} of the crop-development stage was found by averaging the $K_{cb\ ini}$ and $K_{cb\ mid}$ values; likewise, the late-season K_{cb} was determined as the average value of $K_{cb\ mid}$ and $K_{cb\ end}$. Results are summarized in Table 4. Differences between the observed and estimated transpiration were similar with methods 1 and 2. Errors computed with the Allen and Pereira procedure (2009) were larger, which

Table 4
Mean ET_c, mean ET_o for the growth stages and the difference between estimated transpiration (for three method of estimation) and observed transpiration.

Growth stages	Mean ET_c[a] mm d^{-1}	Mean ET_c mm d^{-1}	Observed transpiration[b] (T) mm d^{-1}			Estimated K_{cb}			Difference between estimated transpiration (T_e) - T mm d^{-1}								
						Methods			T_e (method 1)[c]			T_e (method 2)[d]			T_e (method 3)[e]		
			Lys 1	Lys 2	Lys 3	1	2	3	Lys 1	Lys 2	Lys 3	Lys 1	Lys 2	Lys 3	Lys 1	Lys 2	Lys 3
Initial	0.14	1.32	0.11	0.16	0.08	0.08	0.17	0.28	−0.01	−0.06	0.02	0.11	0.06	0.14	0.26	0.21	0.29
Crop-development	1.09	4.39	1.07	1.16	0.81	0.23	0.23	0.37	−0.08	−0.17	0.18	−0.08	−0.17	0.18	0.55	0.46	0.81
Mid-season	0.65	1.57	0.58	0.72	0.58	0.38	0.35	0.45	0.02	−0.12	0.02	−0.04	−0.18	−0.04	0.13	−0.01	0.13
Late-season	0.32	0.96	0.33	0.30	0.28	0.23	0.33	0.40	−0.11	−0.08	−0.06	−0.01	0.02	0.04	0.05	0.08	0.10

[a] Mean ET_c value of observed data for the three lysimeter, for the growth stage.
[b] Mean transpiration value for each lysimeter, for the growth stage.
[c] Method 1: K_{cb} value as a function of DPGI; $T_e = ET_o \times K_{cb}$. Where $K_{cb\ ini} = 0.08$, $K_{cb\ crop\text{-}development} = 0.23$, $K_{cb\ mid} = 0.38$ and $K_{cb\ late\text{-}season} = 0.23$.
[d] Method 2: K_{cb} as a function of FIR; $T_e = ET_o \times K_{cb}$. Where $K_{cb\ ini} = 0.17$, $K_{cb\ crop\text{-}development} = 0.23$, $K_{cb\ mid} = 0.35$ and $K_{cb\ late\text{-}season} = 0.33$.
[e] Method 3: K_{cb} of Allen and Pereira (2009); $T_e = ET_o \times K_{cb}$. Where $K_{cb\ ini} = 0.28$, $K_{cb\ crop\text{-}development} = 0.37$, $K_{cb\ mid} = 0.45$ and $K_{cb\ late\text{-}season} = 0.40$.

is to be expected because the relationships of methods 1 and 2 were obtained from the observed data. The maximum difference between observed transpiration and estimated transpiration with method 1 and method 2 was 0.18 mm, 18% error for the crop development stage. Considering that in commercial orchards all plants are irrigated with the same target despite very large variability in plant development, the potential errors in estimating daily crop evapotranspiration with the proposed relationships do not seem very large.

3.8. Considerations about the studied K_{cb} relationship

This study was conducted using three containerized trees under non-limiting water conditions in a sub-humid climate. Previous studies on olive evapotranspiration (i.e., Testi et al., 2004; Er-Raki et al., 2010; Pôças et al., 2015) have reported different approaches to evaluate this process in both young and well-stablished orchards but under semi-arid conditions. Despite this climatic difference, the range of basal crop coefficients generated in this study is of similar magnitude to those reported by other authors and exhibit similar seasonal patterns.

Evaporation losses, compared to the values obtained in semi-arid conditions, were smaller under the conditions of this study, mainly because of the small wetted area created by the drippers versus different irrigation methods. Clearly, evaporation losses will be much greater than in the study under typical olive production conditions of Uruguay, with high rainfall. Procedures such as those proposed by Pereira (2004) and Allen et al. (1998) will need to be used to develop evaporation estimates under typical production conditions. On the other hand, seasonal patterns of our measured K_{cb} (Figs. 7 and 8) should be to be close to those in well-established and managed commercial orchards of about the same age as in our experiment. In addition, specific K_{cb} values, which will depend on the size of the tree, could be obtained from the K_{cb}-FIR relationship (Fig. 10), if such data were available. As mentioned earlier, the proposed linear equation for K_{cb} as a function of FIR (Fig. 10) appears to be a better method to predict the K_{cb} coefficient than K_{cb} as a function of DPGI (Fig. 8) since the FIR takes into account the size of the canopy and foliage density. However, at this point in time, if can only be used within the range of FIR values measured in this experiment, 0.05 to 0.36 (Fig. 10).

4. Conclusions

One of the main doubts concerning to olive irrigation management in humid areas is whether the patterns of water demand would be similar to those obtained in semi-arid zones. These concerns become more tenuous when considering young olive trees. These doubts became more extensible when it came to young plants. The seasonal variation of the transpiration described by the basal crop coefficient (K_{cb}) was confirmed in young olive trees under humid conditions. This variation had a similar pattern to that reported for olive-producing regions with Mediterranean climate.

Variation of the basal crop coefficient was satisfactorily explained by measured canopy light interception (FIR) and a linear regression model was presented for K_{cb} as a function of FIR. The proposed model could be used to improve K_{cb} estimation for irrigation management purposes of young olive orchards. Additional research is needed to refine the K_{cb} relationship between the fractions of radiation interception by the canopy. Development of reflection indices using remote sensors would also facilitate collection of canopy data for K_{cb} estimation.

Acknowledgments

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In memory of Prof. Mario García Petillo, from Universidad de la República, Uruguay, who led the experimental work and encouraged us with his enthusiasm for research.

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References

Agam, N., Cohen, Y., Berni, J.A.J., Alchanatis, V., Kool, D., Dag, A., Yermiyahu, U., Ben-Gal, A., 2013. An insight to the performance of crop water stress index for olive trees. Agric. Water Manag. 118, 79–86.
Agam, N., Segal, E., Peeters, A., Levi, A., Dag, A., Yermiyahu, U., Ben-Gal, A., 2014. Spatial distribution of water status in irrigated olive orchards by thermal imaging. Precis. Agric. 15, 346–359.
Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and drainage paper no. 56. FAO, Rome, Italy, pp. 300.
Allen, R.G., Pereira, L.S., 2009. Estimating crop coefficients from fraction of ground cover and height. Irrig. Sci. 28, 17–34.
Allen, R.G., Pereira, L.S., Howell, T.A., Jensen, M.E., 2011. Evapotranspiration information reporting: I. Factors governing measurements accuracy. Agric. Water Manage. 98, 899–920.
ASOLUR, 2015. http://www.asolur.org.uy/s/es/cifras. (Accessed October 2015).
Ayars, J.E., Johnson, R.S., Phene, C.J., Trout, T.J., Clark, D.A., Mead, R.M., 2003. Water use by drip-irrigated late-season peaches. Irrig. Sci. 22, 187–194.
Ben-Gal, A., Kool, D., Agam, N., van Halsema, G.E., Yermiyahu, U., Yafe, A., Presnov, E., Erel, R., Majdop, A., Zipori, I., Segal, E., Rüger, S., Zimmermann, U., Cohen, Y., Alchanatis, V., Dag, A., 2010. Whole-tree water balance and indicators for short-term drought stress in non-bearing "Barnea" olives. Agric. Water Manage. 98, 124–133.
Boland, A., Mitchell, P.D., Jerie, P.H., Goodwin, I., 1993. The effect of regulated deficit irrigation on tree water use and growth of peach. J. Hortic. Sci. 68 (2), 261–274.
Boland, A., Jerie, P.H., Mitchell, P.D., Goodwin, I., 2000. Long-term effects of restricted root volume and regulated deficit irrigation on peach: II. Productivity and water use. J. Am. Soc. Hortic. Sci. 125 (1), 143–148.
Bonachela, S., Orgaz, F., Villalobos, F., Fereres, E., 2001. Soil evaporation from drip irrigated olive orchards. Irrig. Sci. 20, 65–71.
Bryla, D.R., Trout, T.J., Ayars, J.E., 2003. Growth and production of young peach trees irrigated by furrow, microjet, surface drip, or subsurface drip systems. Hortic. Sci. 38

(6), 1112–1116.
Carr, M.K.V., 2013. The water relations and irrigation requirements of olive (*Olea europea* L.): a review. Exp. Agric. 49 (4), 597–639.
Casanova, S., 2008. Morfosiologia da cultura de batata submetida a diferentes regimes hídricos. dissertacao Curso de Mestrado da Universidade Federal de Santa María, RS, Brasil.
Castaño, J.P., Giménez, A., Ceroni, M., Furest, J., Aunchayna, R., 2011. Caracterización agroclimática del Uruguay 1980-2009. INIA Serie Técnica 193. Noviembre de 2011.
Connor, D.J., 2005. Adaptation of olive (Olea europaea L.) to water-limited environments. Aust. J. Agric. Res. 56 (11), 1181–1189. https://doi.org/10.1071/AR05169.
Di Rienzo, J.A., Casanoves, F., Balzarini, M.G., Gonzalez, L., Tablada, M., Robledo, W., 2014. InfoStat 2014. Grupo InfoStat, FCA. Universidad de Córdoba, Argentina.
Doorenbos, J., Pruitt, W.O., 1977. Crop Water Requirements. Irrigation and Drainage Paper No. 24 (rev.). FAO, Rome, pp. 144.
FAO, 2015. FAOSTAT Crops. (Accessed October 2015). http://www.fao.org/faostat/en/#data/QC/visualize.
Er-Raki, S., Chehbouni, A., Boulet, G., Williams, D.G., 2010. Using the dual approach of FAO-56 partitioning ET into soil and plant components for olive orchards in a semi-arid region. Agric. Water Manage. 97, 1769–1778.
Fereres, E., Pruitt, W.O., Beutel, J.A., Henderson, D.W., Holzapfel, E., Shulbach, H., Uriu, K., 1981. ET and drip irrigation scheduling. In: Fereres, E. (Ed.), Drip Irrigation Management. University of California. Div. of Agric. Sci. no. 21259, pp. 8–13.
Fereres, E., Villalobos, F.J., Orgaz, F., Testi, L., 2011. Water requirements and irrigation scheduling in olive. Acta Hortic. (ISHS) 888, 31–40.
Fernández, J.E., Moreno, F., 1999. Water use by olive tree. J. Crop Prod. 2, 101–162.
García-Ortiz, A., Humanes, J., Pastor, M., Morales, J., Fernández, A., 2008. Poda. In: Barranco, D., Fernandez-Escobar, R., Rallo, L. (Eds.), El cultivo del olivo. Ediciones Mundi-Prensa, Barcelona, pp. 389–433.
Girona, J., Luna, A., Arbonés, A., Mata, M., Rufat, J., Marsal, J., 2002a. Young olive trees responses (*Olea europea*, cv "Arbequina") to different water supplies. Water function determination. Acta Hortic. 586, 277–280.
Girona, J., Mata, M., Fereres, E., Goldhamer, D.A., Cohen, M., 2002b. Evapotranspiration and soil water dynamics of peach tees under water deficits. Agric. Water Manage. 54, 107–122.
Girona, J., Marsal, J., Mata, M., del Campo, J., 2004. Pear Crop coefficients obtained in a large weighing lysimeter. Acta Hortic. 664, 277–281.
Girona, J., del Campo, J., Mata, M., Lopez, G., Marsal, J., 2011. A comparative study of apple and pear tree water consumption measured with two weighing lysimeters. Irrig. Sci. 29 (1), 55–63.
Goldhamer, D.A., Dunai, J., 1994. Irrigation requirements of olive trees and responses to sustained deficit irrigation. Acta Hortic. 356, 172–175.
Grattan, S.R., Berenguer, M.J., Connell, J.H., Polito, V.S., Vossen, P.M., 2006. Olive oil production as influenced by different quantities of applied water. Agric. Water Manage. 85, 133–140.
Gucci, R., Fereres, E., 2012. Olive. In: Steduto, P., Hsiao, T., Fereres, E., Raes, D. (Eds.), Crop Yield Response to Water. FAO Irrigation and Drainage Paper No. 66. FAO, Rome, Italy, pp. 300–313.
Haverkamp, R., Vauclin, M., Vachaud, G., 1984. Error analysis in estimating soil water content from neutron probe measurements: 1. Local standpoint. Soil Sci. 137 (2), 78–90.
Hunsaker, D., Pinter Jr, P.J., Cai, H., 2002. Alfalfa basal crop coefficients for FAO-56 procedures in the desert regions of the southwestern U.S. Am. Soc. Agric. Eng. 45 (6), 1799–1815 ISSN 0001-2531.
Hunsaker, D., Fitzgerald, A.N., French, A.N., Clarke, T.R., Ottman, M.J., Pinter Jr, P.J., 2007. Wheat irrigation management using multispectral crop coefficients: I. Crop evapotranspiration prediction. Trans. ASABE 50 (6), 2017–2033 ISNN 0001-2351.
Iancu, M., 1997. Plum tree water consumption determined in lysimeter as compared to other methods. Acta Hortic. (ISHS) 449 (1), 107–112.
Jensen, M.E., Burman, R.D., Allen, R.G., 1990. Evapotranspiration and Irrigation Water Requirements. ASCE Manual and Reports Nº 70. ASCE, New York.
Johnson, R.S., Ayars, J.E., Trout, T.J., Mead, R., Phene, C., 2000. Crop coefficients for mature peach trees are well correlated with midday canopy light interception. Acta Hortic. (ISHS) 537, 455–460.
Johnson, R.S., Ayars, J.E., Hsiao, T., 2004. Improving a model for predicting peach tree evapotranspiration. Acta Hortic. (ISHS) 664, 341–346.
Klocke, N.L., Martín, D.L., Todd, R.W., De Haan, D.L., Polymenopoulus, A.D., 1990. Evaporation measurements and predictions from soils under crop canopies. Am. Soc. Agric. Eng. 1590–1596 0001-2351/90/3305.
López-Olivari, R., Ortega-Farías, S., Poblete-Echeverría, C., 2016. Partitioning of net radiation and evapotranspiration over a superintensive drip-irrigated olive orchard. Irrig. Sci. 34, 17–31.
Moriana, A., Villalobos, F., Fereres, E., 2002. Stomatal and photosynthetic responses of olive (*Olea europea* L.) leaves to water deficits. Plant Cell Environ. 25, 395–405.
Moriana, A., Orgaz, F., Pastor, M., Fereres, E., 2003. Yield responses of mature olive orchard to water deficits. J. Am. Soc. Hortic. Sci. 123 (3), 425–431.
Orgaz, F., Fereres, E., 2008. Riego. In: Barranco, D., Fernandez-Escobar, R., Rallo, L. (Eds.), El cultivo del olivo. Ediciones Mundi-Prensa, Barcelona, pp. 337–362.
Paço, T.A., Ferreira, M., Conceiçao, N., 2006. Peach orchard evapotranspiration in a sandy soil: comparison between eddy covariance measurements and estimates by the FAO 56 approach. Agric. Water Manage. 85, 305–313.
Paço, T.A., Paredes, P., Pereira, L.S., Silvestre, J., Santos, F., 2019. Crop coefficients and transpiration of a super intensive arbequina olive orchard using the dual kc approach and the Kcb computation with the fraction of ground cover and height. Water 11, 383. https://doi.org/10.3390/w11020383.
Pereira, L.S., 2004. Necessidades de Água e Métodos de Rega. Publicações Europa-América, Lisboa, pp. 312.
Pôças, I., Paço, T.A., Paredes, P., Cunha, M., Pereira, L.S., 2015. Estimation of actual crop coefficients using remotely sensed vegetation indices and soil water balance modelled data. Remote Sens. 7 (3), 2373–2400. https://doi.org/10.3390/rs70302373.
Puppo, L., García, C., Girona, J., García Petillo, M., 2014. Determination of young olive-tree water consumption with drainage lysimeters. J. Water Resour. Prot. 6, 841–851.
Snyder, R.L., Ferreira, M.I., Shackel, K.A., 2000. A crop coefficient model for trees and vines. Acta Hort. 537, 549–556 ISHS 2000.
Stevenson, D.S., 1989. Irrigation subsurface return flows and water use in lysimeter containing apple trees. Canadian J Soil Science 69, 769–778.
Task Committee on Revision of Manual 70, 2016. In: Jensen, Marvin E., Allen, Richard (Eds.), Evaporation, Evapotranspiration, and Irrigation of Water Requirements, second edition. pp. 744.
Testi, L., Villalobos, F.J., Orgaz, F., 2004. Evapotranspiration of a young irrigated olive orchard in southern Spain. Agric. For. Meteorol. 121, 1–18.
Testi, L., Villalobos, F.J., Orgaz, F., Fereres, E., 2006. Water requirements of olive orchards: I simulation of daily evapotranspiration for scenario analysis. Irrig. Sci. 24, 69–76.
Villalobos, F.J., Orgaz, F., Testi, L., Fereres, E., 2000. Measurement and modeling of evapotranspiration of olive (*Olea europea* L.) orchards. Eur. J. Agron. 13, 155–163.
Villalobos, F.J., Testi, L., Orgaz, F., García-Tejera, O., Lopez-Bernal, A., González-Dugo, M.V., Ballester-Lurbe, C., Castel, J.R., Alarcón-Cabañero, J.J., Nicolás-Nicolás, E., Girona, J., Marsal, J., Fereres, E., 2013. Modelling canopy conductance and transpiration of fruit trees in Mediterranean areas: a simplified approach. Agric. For. Meteorol. 171–172, 93–103.
Williams, L.E., Ayars, J.E., 2005. Grapevine water use and crop coefficient are linear functions of the shaded area measured beneath the canopy. Agric. For. Meteorol. 132, 201–211.
Wraith, J., Or, D., 1998. Nonlinear parameter estimation using spreadsheet software. J. Nat. Resour. Life Sci. Educ. 27, 13–19.
Wright, J.L., 1982. New evapotranspiration crop coefficients. J. Irrig. Drain. Div. 108 (1), 57–74.
Yang, P., Hu, H., Tian, F., Zhang, Z., Dai, C., 2016. Crop coefficient for cotton under plastic mulch and drip irrigation based on eddy covariance observation in an arid area of northwestern China. Agric. Water Manag. 171, 21–30.

4. MATERIALES Y MÉTODOS COMPLEMENTARIO

La ET_c de plantas jóvenes de olivo fue determinada mediante lisimetría, efectuando un balance hídrico (BH) en condiciones controladas, midiendo cada uno de los términos involucrados en la siguiente ecuación.

$$ET_c = R - D \pm \Delta H_s$$

donde ET_c es la evapotranspiración real del olivo, R es el volumen de riego, D es el volumen de drenaje y AH_s es el cambio en el volumen de agua del suelo.

La única entrada de agua en el experimento fue el riego, mientras que las salidas de agua fueron el drenaje y la ET_c.

La estructura “rain out shelter” con cierre automático mantuvo protegido al experimento de las lluvias mayores a 3 mm. Los datos correspondientes al día en que el shelter se mantuvo cerrado y el día posterior fueron descartados debido a las posibles alteraciones en el proceso de evapotranspiración por la modificación de los parámetros climáticos. También se descartaron los datos correspondientes al día anterior al cierre de la estructura para evitar las lluvias menores a 3 mm, que pudiesen haber ocurrido el día anterior al cierre del “rain out shelter”.

El riego aplicado se registró controlando el tiempo de aplicación de los goteros. Los goteros fueron del tipo autocompensados, con esta característica se aseguró que no hubiese alteración del caudal por cambios en la presión operativa de los goteros. No obstante el caudal fue chequeado periódicamente durante el experimento, colectando y midiendo el caudal de cada gotero durante 10 minutos. La precisión del instrumento para medir el caudal de los goteros y por lo tanto el volumen de entrada fue de 0,001 L.

Toda el agua aplicada entró al suelo de relleno dado que la estructura de los lisímetros presentaba un borde de 10 cm por encima de la superficie del suelo, que impidió el escurrimiento desde y hacia el lisímetro.

La precisión del instrumento para medir el volumen de salida (volumen de drenaje) fue de 0,01 L.

Debido a que los lisímetros de drenaje, pueden presentar como fuente de error la demora en la evacuación del agua libre por los cambios de retención de agua del suelo (Aboukhaled et al., 1981), se midió diariamente el drenaje asegurando el registro total del agua de salida en cada una de las unidades experimentales (lisímetros) y se registró la variación de humedad en todos los horizontes del suelo de relleno (ΔH_s).

El movimiento del agua en profundidad fue monitoreado a través de medidas efectuadas con la sonda de neutrones dos veces por semana en cada unidad experimental y en cada profundidad. La sonda fue calibrada con el método gravimétrico cada 20 cm de profundidad (donde se constató el cambio de horizontes en el suelo de relleno) a partir de pares de punto para todo el rango de humedad, desde saturación hasta punto de marchitez permanente, según Haverkamp et al. (1984). De esta forma se obtuvo una calibración con 29 observaciones para cada profundidad.

Se determinaron valores de ET_c promedio para 7 a 15 días, período indicado para la obtención de valores confiables para este tipo de lisímetros (Aboukhaled et al., 1981).

Las medidas de ET_c de la planta de 4 años de edad (planta de mayor edad al momento de su plantación en los lisímetros) comenzaron a partir de diciembre del año 1 del experimento después de recuperar su densidad de follaje luego del estrés post trasplante. Mientras que los datos correspondientes a las plantas de 2 años de edad y a las directas del vivero se colectaron inmediatamente a la fecha de trasplante (14 de setiembre de 2010).

Para la estimación del K_{cb} (segundo artículo) se eliminaron las dos plantas más jóvenes (directas del vivero al inicio del experimento) debido a que se constató un comportamiento atípico al resto del ensayo en la relación entre ET_c y las medidas de la fracción de intercepción solar (FIR). Asimismo se renombraron las plantas como sigue: la planta ubicada en el lisímetro 2 pasó a llamarse Lys 1 (dos años al inicio del experimento); la planta ubicada en el lisímetro 10 pasó a llamarse Lys 2 (cuatro años al inicio del experimento) y la planta ubicada en el lisímetro 11 pasó a llamarse Lys 3 (dos años al inicio del experimento). Debido a las características de cultivo perenne del olivo y para la mejor interpretación de los resultados, en el segundo artículo los días del ciclo se nombraron como DPGI (días después del inicio del crecimiento), donde DPGI=1 corresponde al 11 de julio, fecha a partir de la cual comenzó a aumentar la ET_c, en respuesta al crecimiento vegetativo y al aumento de la temperatura en nuestro hemisferio.

En este estudio se cuantificó la evaporación directa desde el suelo con microlisímetros (Paço et al. 2006, Bonachela et al. 2001) ubicados en la zona húmeda (expuesta y bajo copa). Se registró la variación del K_e en el proceso de secado de una semana en la mancha húmeda para ambas zonas, expuesta y bajo copa. Se determinó el tamaño de la mancha húmeda en cada lisímetro mediante una cuadrícula con la proyección horizontal de la copa al mediodía, así como la fracción expuesta y bajo copa de la misma. Se monitoreó el tamaño de las plantas cada tres meses.

Se descontó a la ET_c medida en cada lisímetro el componente de evaporación directa, contemplando en el valor del K_e los días entre riegos consecutivos y la proporción de la mancha húmeda y expuesta, y húmeda bajo copa, en el marco de distanciamiento entre plantas (5,5 m x 2,5 m).

El coeficiente basal del cultivo fue ajustado mediante el modelo de cuatro segmentos sugerido por FAO-56 únicamente para la segunda temporada de evaluación, debido a que durante la primera temporada no se contó con las observaciones correspondientes al inicio de la misma y las plantas mostraron tamaños muy diferentes.

5. RESULTADOS Y DISCUSIÓN COMPLEMENTARIO

La baja incertidumbre en los distintos términos del BH junto con el control de calidad de los datos en base el contenido de humedad en la profundidad radical y estado de las plantas (según se indicó en Materiales y Métodos de ambos artículos publicados) permitieron trabajar con datos fiables para la determinación de la ET_c, asegurando la condición de no estrés hídrico necesaria para la determinación del K_c y K_{cb} . Si tenemos en cuenta que L m^{-2} equivalen a mm, la precisión de los registros de la evapotranspiración en nuestro estudio debería ser mayor a 0,01 mm. Esto último debido a que la menor precisión de los volúmenes medidos fue de 0,01 L y a que el área de evapotranspiración durante todo el experimento siempre fue mayor a 1 m^2 (área del lisímetro 1,71 m^2 más el área de la copa de las plantas por fuera del área del lisímetro).

5.1 EVAPOTRANSPIRACIÓN

La evapotranspiración, en L d^{-1} o en mm d^{-1}, siguió el mismo patrón estacional que la demanda atmosférica descrita por la ET_o en las cinco plantas del estudio (Figura 6, 7 y 8 del primer artículo), con los valores máximos en los meses de diciembre, enero y primera mitad de febrero y los mínimos ubicados en junio, julio y agosto.

Los datos de ET_o de los dos años de evaluación (2010-2011 y 2011-2012) fueron analizados dentro de una serie climática (1997-2018) para INIA Las Brujas. Los promedios semanales de los dos años del estudio fueron superados solo por un año de la serie, por lo tanto se los caracterizó como años de alta demanda atmosférica para la zona sur del país. Estos valores fueron entre 5-15 % más bajos que los reportados para climas áridos en otros estudios en los que se determinó la ET_c de olivos (Grattan et al. 2006, Testi et al. 2004).

El valor más alto de consumo explicado por la ET_c correspondió a la planta de 6 años, con un porcentaje de cobertura de suelo de 50 % (relación entre área de la copa x 100/marco de separación entre plantas). El valor promedio para 7 a 15 días de este parámetro fue 29 L d^{-1}, equivalente a 2,1 mm d^{-1} al referirlo al marco de separación entre plantas (5,5 m x 2,5 m) (Figura 8 del primer artículo).

5.2 COEFICIENTE DE CULTIVO

El coeficiente de cultivo (K_c) mostró una marcada estacionalidad, con los menores valores ubicados en la segunda quincena de julio, agosto y comienzos de setiembre y los valores máximos a mediados de abril y mayo (Figura 1). Este patrón es diferente al de cultivos anuales y al de frutales de hoja caduca donde el valor máximo corresponde a los meses de verano luego que se completa el crecimiento vegetativo en los primeros y se renueva totalmente el follaje en los segundos.

En climas con lluvias frecuentes como el de Uruguay, este patrón se vería distorsionado en cada evento al humedecerse toda la superficie del suelo, pudiendo alcanzar valores de K_c cercanos a 1 o superiores debido al incremento del componente de evaporación directa (Puppo y García Petillo, 2010). En el mismo sentido, en climas de tipo mediterráneo, los valores más altos de K_c para olivo han sido reportados para la estación lluviosa (Gucci y Fereres 2012, Testi et al. 2004).

Sin embargo, en este estudio el componente de evaporación directa estuvo limitada únicamente al suelo humedecido por los goteros y quedó en evidencia el patrón de K_c del olivo (Figura 1), que en este caso estuvo controlado mayormente por la conductancia estomática cuyo patrón estacional fue reportado por Villalobos et al. (2000) y Moriana y Fereres (2002).

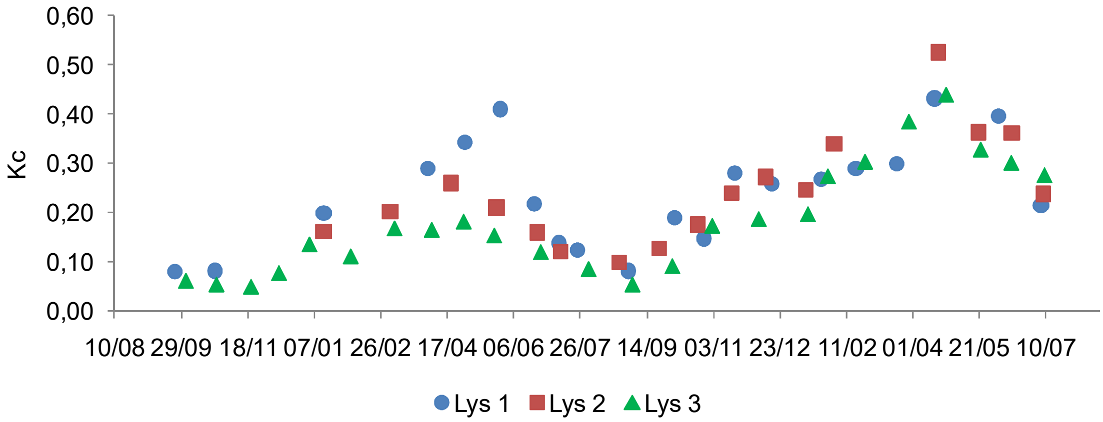


Figura1. Coeficiente de cultivo K_c para las dos temporadas de evaluación 2010-2011 y 2011-2012.

Los valores de K_c 2011-2012 son mayores a los correspondientes a la temporada anterior, en respuesta al mayor tamaño de las plantas (Figura 4 del segundo artículo).

De todas formas con la finalidad de separar totalmente la transpiración de la evaporación directa, se ajustó el coeficiente de cultivo basal (K_{cb}), separando el componente de evaporación directa producida a partir de la zona húmeda de los goteros, descripta por el coeficiente de evaporación (K_e).

5.3 COEFICIENTE BASAL DEL CULTIVO Y COEFICIENTE DE EVAPORACIÓN

Con la finalidad de poder estimar la ET_c del olivo para montes con distintos marcos de plantación, distinta estructura de plantas y distintos patrones de mojado resultantes del diseño agronómico de los sistemas de riego localizado, se ajustó en forma independiente el K_{cb} y para determinar la influencia del tamaño de la planta sobre este coeficiente se ajustó la relación K_{cb} con la fracción de intercepción de la radiación (FIR) ocasionada por la copa de las plantas. Para poder estimar la ET_c del olivo y hacer un correcto manejo del riego, luego habría que calcular el K_e aplicando el método propuesto por FAO-56, que se basa en aplicar un balance hídrico en la capa de suelo más superficial, húmeda y expuesta a la radiación y al viento (Puppo y García Petillo 2010, Allen et al. 2005, 1998) y se fundamenta en la teoría bi-fásica de la evaporación desde el suelo (Allen et al. 2005, 1998). Con esa metodología se contabilizaría la pérdida de agua desde la zona mojada de los goteros (dependiente de su caudal y espaciamiento) y desde la superficie total del suelo en cada evento de lluvia.

En nuestro estudio la evaporación se determinó mediante microlisímetros. Esta metodología según Klocke et al. (1990) podría generar una ligera sobreestimación debida al hecho que los microlisímetros se mantuvieron siempre en la misma ubicación durante la determinación y estaría ocasionado por la interrupción de la absorción de las raíces en el suelo de relleno de los microlisímetros. A pesar de ello, se decidió mantener los microlisímetros en el mismo lugar (Paço et al. 2006, Bonachela et al. 2001) para que la variabilidad espacial de la humedad del suelo resultante de cambiar los microlisímetros de lugar no distorsionase la evolución de la humedad durante el ciclo de secado.

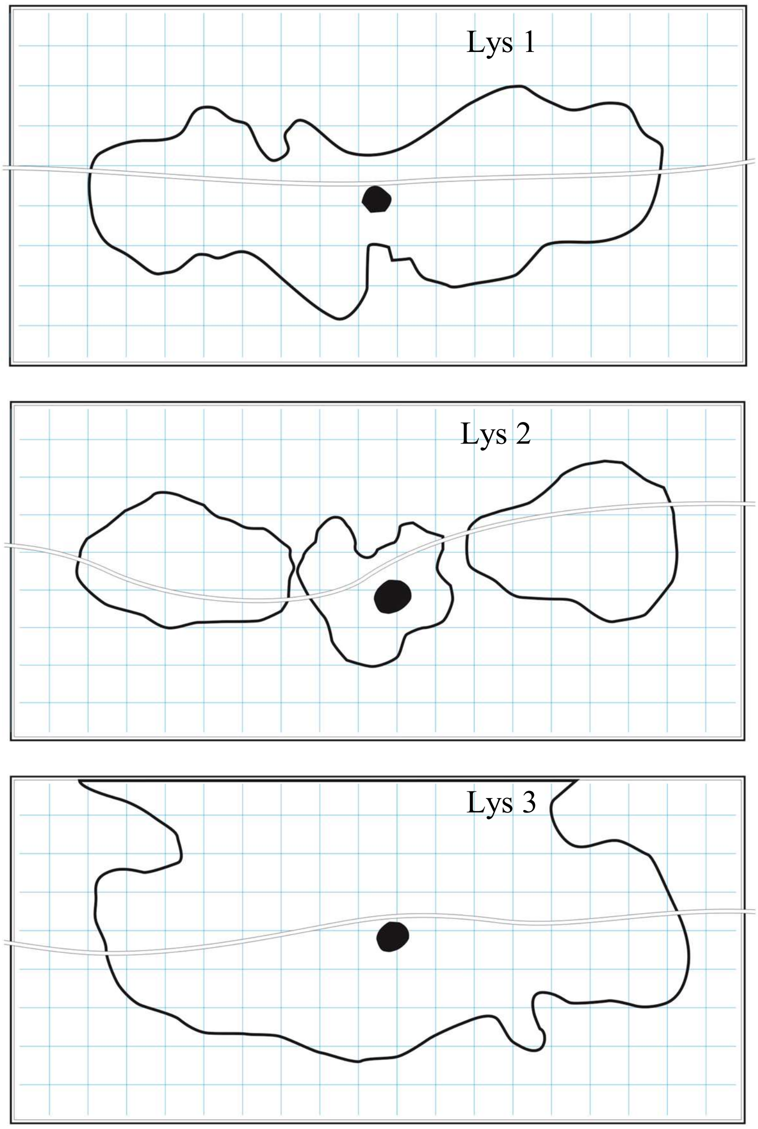
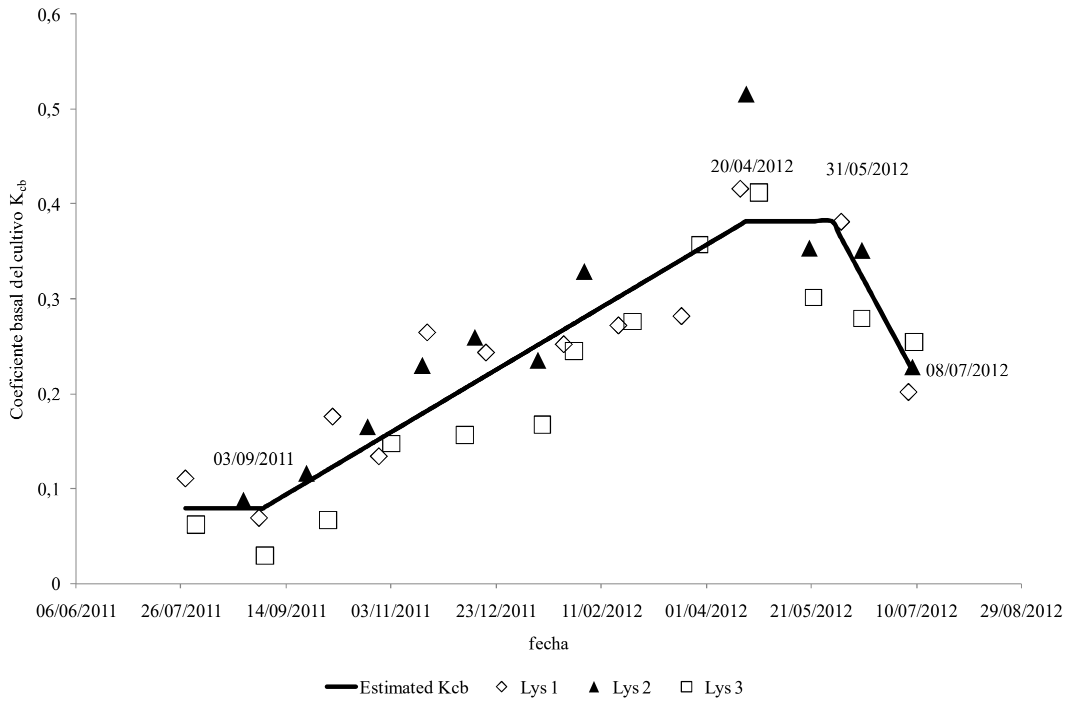


Figura 2. Mancha húmeda monitoreada en las tres plantas, sobre la superficie del suelo de relleno de los lisímetros.

Las tres plantas fueron regadas en exceso para producir drenaje, pero con una cantidad de agua proporcional a la demanda atmosférica (ET_o x 0.7 x Kr). Esto determinó que el tamaño de la mancha húmeda se mantuviese estable en el tiempo. El tamaño de la mancha húmeda estuvo siempre en el entorno de 0,49, 0,37 y 0,86 m^2 para el Lys 1, Lys 2 y Lys 3, respectivamente (Figura 2). El mayor tamaño de la mancha en el Lys 3 se debió al menor tamaño de la planta, con un menor consumo de agua en comparación a las otras dos.

El K_e para el ciclo de secado posterior al riego se obtuvo para la zona expuesta y la zona bajo copa de la mancha húmeda (Figura 2 del segundo artículo). Luego se ajustaron los valores de K_e promedio mensuales, referidos al marco de separación entre plantas. Los valores de estos coeficientes permanecieron casi constantes en



las dos temporadas de evaluación, entre 0,02 y 0.04, un orden de magnitud menor a los K_{cb} (Figura 7 del segundo artículo).

Figura 3. Variación de K_{cb} en función del día del año, datos combinados de tres plantas. La línea representa el modelo de cuatro tramos FAO-56

Fue posible describir la evolución de K_{cb} durante la segunda temporada acorde al modelo propuesto por FAO-56 (Figura 3) con un ajuste satisfactorio (R^2=0,83). Los menores valores de K_{cb} se observaron durante 54 días hasta el 3 de setiembre, momento a partir del cual el K_{cb} aumentó hasta el 20 de abril con una pendiente determinada por el coeficiente de regresión b1= 0.0013 día^{-1} y se mantuvo constante con un valor máximo de 0,38 hasta el 31 de mayo, momento a partir del cual comenzó a descender con una pendiente determinada por el coeficiente de regresión b2= - 0.004 día^{-1}.

En la Tabla 1 se presentan los valores de K_{cb} promedio para cada estación, este patrón durante las estaciones coincide con el informado por Gucci y Fereres (2012), quienes indicaron que la transpiración relativa (descrita por el K_{cb}) de los olivos muestra una variación marcada, con valores mínimos a fin del invierno e inicios de la primavera y valores máximos a principios del otoño. En el mismo sentido pero estudiando la conductancia estomática de los olivos, Moriana y Fereres (2002) encontraron que la conductancia estomática mostró variación estacional alcanzando sus valores máximos en otoño. Si bien en nuestro estudio no se realizaron medidas de conductancia estomática otros autores han sugerido que el valor de K_{cb} de los árboles perennes y particularmente de los olivos está controlado principalmente por la conductancia estomática (Fereres et al. 2011, Villalobos et al. 2000).

Tabla 1. Coeficiente basal del cultivo promedio para cada estación del año, para plantas con un desarrollo de entre 24 y 41 %

	Invierno	Primavera	Verano	Otoño
K_{cb} cobertura (24-41 %)	0,08	0,16	0,28	0,36

Como se puede apreciar el valor más alto de K_{cb} se obtuvo en otoño (segunda quincena de abril y mayo). Este patrón en los valores de K_{cb}, determinó la particularidad de que no haya coincidencia entre el valor más alto de K_{cb} con los valores más altos de ET_o, esto derivó en valores más bajos de transpiración que los que podrían resultar si ambos valores coincidieran para una estación como sucede en muchos de los cultivos anuales y frutales de hoja caduca.

6. CONCLUSIONES GENERALES

Los resultados de evapotranspiración y coeficientes K_c y K_{cb} presentados aquí son representativos de montes jóvenes, donde la radiación recibida por las plantas no se vió afectada por el sombreado de las plantas contiguas y donde los fenómenos aerodinámicos influyen individualmente en cada planta.

El consumo de agua en L d^{-1} estuvo fuertemente relacionado con el tamaño de la planta. El porcentaje de cobertura del suelo por la copa fue el parámetro que explicó la mayor variación en el consumo de agua de la planta.

Se encontró una relación lineal positiva entre el K_c de los meses de verano y el porcentaje de cobertura del suelo por la copa. Esta relación solo se aplica a períodos sin lluvia, con el patrón de mojado causado por el número y caudal de los goteros usados en el experimento y con plantas de hasta 46 % de porcentaje de cobertura del suelo por la copa.

La variación estacional de la transpiración descrita por el coeficiente basal (K_{cb}) se confirmó para olivos jóvenes en condiciones húmedas. Esta variación tuvo un patrón similar al reportado para las regiones productoras de olivo con clima mediterráneo.

La variación del coeficiente basal se explicó satisfactoriamente mediante la fracción de la intercepción de la radiación por la copa (FIR) y se presentó un modelo de regresión lineal para K_{cb} en función de FIR. El modelo propuesto podría utilizarse para mejorar la estimación del K_{cb} para gestionar el riego de los olivares jóvenes. Se necesita investigación adicional para mejorar esta relación. El desarrollo de índices de reflexión utilizando sensores remotos podía facilitar la recopilación de datos de intercepción de radiación por la copa para la estimación del K_{cb}.

El riego a demanda asociado con un buen drenaje del suelo resultó en un rápido crecimiento de las plantas jóvenes. En una temporada de crecimiento, en su transición de 3 a 4 años, las plantas intermedias duplicaron su área de copa y quintuplicaron su volumen. La planta más grande aumentó el área de la copa y del volumen, en 36 % y 40

% respectivamente, en su transición de 5 a 6 años. Este rápido crecimiento aceleraría la entrada del monte a plena producción, llegando en una edad productiva más temprano.

7. BIBLIOGRAFÍA

Aboukhaled A, Alfaro J, Smith M. 1981. Los lisímetros. FAO. Paper 39. Roma. Italia. pp 68.

Agam N, Segal E, Peeters A, Levi A, Dag A, Yermiyahu U, Ben-Gal A. 2014. Spatial distribution of water status in irrigated olive orchards by thermal imaging. Precision Agriculture. 15: 346-359.

Agam N, Cohen Y, Berni JAJ, Alchanatis V, Kool D, Dag A, Yermiyahu U, Ben-Gal A. 2013. An insight to the performance of crop water stress index for olive trees. Agricultural Water Management. 118: 79-86.

Ahumada-Orellana LE, Ortega-Farías S, Searles PS. 2018. Olive oil quality response to irrigation cut-off strategies in a super-high density orchard. Agricultural Water Management. 202: 81-88.

Alegre S, Marsal J, Mata M, Arabonés A, Girona J, Tovar MJ. 2002. Regulated deficit irrigation in olive tres (Olea europaea L. cv. Arbequina) for oil production. Acta Horticulturae. 586: 259-262.

Allen R, Pereira LS, Howell, TA, Jensen ME. 2011. Evapotranspiration information reporting: I. Factors governing measurements accuracy. Agricultural Water Management. 98: 899-920.

Allen R, Pereira LS. 2009. Estimating crop coefficients from fraction of ground cover and height. Irrigation Science. 28: 17-34.

Allen R, Pereira LS, Smith M, Raes D, Wright, J. 2005. FAO-56 Dual crop coefficient method for estimating evaporation from soil and application extensions. Journal of Irrigation and Drainage Engineering. 131(1): 2-13.

Allen R, Pereira LS, Raes D, Smith M. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and drainage. Paper 56. FAO. Rome, Italy. pp 300.

ASOLUR (Asociación Olivícola Uruguaya). Sector olivícola. 2018. http://asolur.org.uy/cifras. Verificado junio 2018.

Ayars JE, Johnson RS, Phene CJ, Trout TJ, Clark DA, Mead RM. 2003. Water use by drip-irrigated late-season peaches. Irrigation Science. 22: 187-194.

Baratta B, Caruso T, Di Marco L, Inglese P. 1986. Effects of irrigation on characteristics of olives in “Nocellara del Belice” variety. Olea. 17: 195-198.

Ben-Gal A, Kool D, Agam N, van Halsema GE, Yermiyahu U, Yafe A, Presnov E, Erel R, Majdop A, Zipori I, Segal E, Rüger S, Zimmermann U, Cohen Y, Alchanatis V, Dag A. 2010. Whole-tree water balance and indicators for short-term drought stress in non-bearing "Barnea" olives. Agricultural Water Management. 98: 124-133.

Blasina y Asociados. Olivicultura uruguaya, en silencioso crecimiento desde hace 10 años. Diario el Observador, 8 de agosto de 2013. https://www.elobservador.com.uy/olivicultura-uruguaya-silencioso-crecimiento-hace-10-anos-n257014.

Boland A, Jerie PH, Mitchell PD, Goodwin I. 2000. Long-term effects of restricted root volume and regulated deficit irrigation on peach: II. Productivity and water use. J American Society Horticultural Science 125(1): 143-148.

Boland A, Mitchell PD, Jerie PH, Goodwin I. 1993. The effect of regulated deficit irrigation on tree water use and growth of peach. Journal of Horticultural Science. 68(2): 261-274.

Bonachela S, Orgaz F, Villalobos F, Fereres E. 2001. Soil evaporation from drip irrigated olive orchards. Irrigation Science. 20: 65-71.

Bryla DR, Trout TJ, Ayars JE. 2003. Growth and production of young peach trees irrigated by furrow, microjet, surface drip, or subsurface drip systems. Horticultural Science. 38(6): 1112-1116.

Capurro MC; Berreta A; García C; Sawchik J; Puppo L. 2017. Rendimiento de la soja en respuesta a distintas dosis y momentos de riego. Agrociencia. 21(2): 65-76.

Carr MKV. 2013. The water relations and irrigation requirements of olive (*Olea europea* L.): A review. Experimental Agriculture. 49(4): 597-639.

Civantos L. 2008. La olivicultura en el mundo y en España. En: Barranco D, Fernández-Escobar R, Rallo L. (Eds.). El cultivo del olivo. Barcelona, España. Ediciones Mundi-Prensa,.19-35.

Connor, DJ. 2005. Adaptation of olive (Olea europaea L.) to water-limited environments. Australian Journal of Agricultural Research. 56(11): 1181-1189. doi:10.1071/AR05169.

Consejo Oleícola Internacional. 2018. Cifras del mercado mundial del aceite de oliva. Producción. http://www.internationaloliveoil.org/estaticos/view/131-world-olive-oil-figures Verificado junio de 2018.

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

Fereres E, Villalobos FJ, Orgaz F, Testi L. 2011. Water Requirements and Irrigation Scheduling in Olive. Acta Horticulturae (ISHS). 888: 31-40.

Fereres E, Pruitt WO, Beutel JA, Henderson DW, Holzapfel E, Shulbach H, Uriu K. 1981. ET and drip irrigation scheduling. In: Fereres E (Ed.) Drip Irrigation Management. University of California. Division of Agriculture Sciences. No. 21259: 8-13.

Fernández JE, Moreno F. 1999. Water use by olive tree. Journal of. Crop Production. 2:101-162.

Fernández JE, Moreno F, Girón I F, Blázquez OM. 1997. Stomatal control of water use in olive tree leaves. Plant and Soil. 190: 179-192.

Fernández-Escobar R, de la Rosa Navarro R, León Moreno L, Gómez JA, Testi L, Orgaz F, Gil-Ribes J, Quesada Moraga E, Trapero Casas A, Msallem M. 2012. Olivae: revista oficial del Consejo Oleícola Internacional. 118: 55-68.

García Petillo M, Castel JR. 2007. Water balance and crop coefficient (Kc) estimation of a citrus orchard in Uruguay. Spanish Journal of Agricultural Research. 5(2): 232-243.

Girona J, del Campo J, Mata M, Lopez G, Marsal J. 2011. A comparative study of apple and pear tree water consumption measured with two weighing lysimeters. Irrigation Science. 29: 55-63.

Girona J, Marsal J, Mata M, del Campo J. 2004. Pear Crop coefficients obtained in a large weighing lysimeter. Acta Horticulturae. 664: 277-281.

Girona J, Mata M, Fereres E, Goldhamer DA, Cohen M. 2002. Evapotranspiration and soil water dynamics of peach tees under water deficits. Agricultural Water Management. 54: 107-122.

Goldhamer DA, Dunai J. 1994. Irrigation requirements of olive trees and responses to sustained deficit irrigation. Acta Horticulturae. 356: 172-175.

Grattan SR, Berenguer MJ, Connell JH, Polito VS, Vossen PM. 2006. Olive oil production as influenced by different quantities of applied water. Agricultural Water Management. 85: 133-140.

Gucci R, Fereres E. 2012. Olive. In: Steduto P., Hsiao T., Fereres E., Raes D. Crop yield response to water. FAO Irrigation and drainage. Paper 66. FAO. Rome, Italy, pp 300-313.

Gucci R, Lodolini EM, Rapoport HF. 2007. Productivity of olive trees with different water status and crop load. Journal Horticultural Science Biotechnology. 82(4): 648-656.

Haverkamp M, Vauclin M, Vachaud G. 1984. Error analysis in estimating soil water content from neutron probe measurements: I. Local standpoint. Soil Science. 137(2): 78-90.

Hunsaker D, Fitzgerald AN, French AN, Clarke TR, Ottman MJ, Pinter PJJr. 2007. Wheat irrigation management using multispectral crop coefficients: I. Crop evapotranspiration prediction. American Society of Agricultural Engineers. 50(6): 2017-2033, ISNN 0001-2351.

Hunsaker D, Pinter PJJr, Cai H. 2002. Alfalfa basal crop coefficients for FAO-56 procedures in the desert regions of the southwestern U.S. American Society of Agricultural Engineers. 45(6): 1799-1815.

Iancu M. 1997. Plum tree water consumption determined in lysimeter as compared to other methods. Acta Horticulturae (ISHS) 449(1): 107-112.

INIA (Instituto Nacional de Investigación Agropecuaria). 2010. Resultados experimentales en olivos. Canelones, Uruguay. Jornada de Divulgación, INIA Las Brujas, 29 de octubre de 2010.

Iniesta F, Testi L, Orgaz F, Villalobos FJ. 2009. The effects of regulated and continuous deficit irrigation on the water use, growth and yield of olive trees. European Journal of Agronomy. 30: 258-265.

Jensen ME, Burman RD, Allen RG. 1990. Evapotranspiration and irrigation water requirements. ASCE (American Society of Civil Engineers) Manual and Reports Nº 70, ASCE, New York, EUA.

Johnson RS, Ayars JE, Hsiao T. 2004. Improving a model for predicting peach tree evapotranspiration. Acta Horticulturae (ISHS). 664: 341-346.

Johnson RS, Ayars JE, Trout TJ, Mead R, Phene C. 2000. Crop coefficients for mature peach trees are well correlated with midday canopy light interception. Acta Horticulturae (ISHS). 537: 455-460.

Klocke NL, Martín DL, Todd RW, De Haan DL, Polymenopoulus AD. 1990. Evaporation measurements and predictions from soils under crop canopies. American Society of Agricultural Engineers 0001-2351/90/3305: 1590-1596.

López-Olivari R, Ortega-Farías S, Poblete-Echeverría C. 2016. Partitioning of net radiation and evapotranspiration over a superintensive drip-irrigated olive orchard. Irrigation Science. 34: 17–31.

Moreno F, Fernández JE, Clothier B, Green SR. 1996. Transpiration and root water uptake by olive trees. Plant and Soil. 184:85-96.

Moriana A, Orgaz F, Pastor M, Fereres E. 2003. Yield responses of a mature olive orchard to water deficits. Journal of the American Society for Horticultural Science. 128(3): 425-431.

Moriana A, Fereres E. 2002. Plant indicators for scheduling irrigation of young olive trees. Irrigation Science. 21: 83-90.

Orgaz F, Fereres E. 2008. Riego. En: Barranco D, Fernandez-Escobar R, Rallo L. (Eds.). El cultivo del olivo. Barcelona, España. Ediciones Mundi-Prensa,. pp 337-362.

Orgaz F, Testi L, Villalobos FJ, Fereres E. 2006. Water requirements of olive orchards-II: determination of crop coefficients for irrigation scheduling. Irrigation Science. 24: 77-84.

Paço TA, Ferreira M, Conceiçao N. 2006. Peach orchard evapotranspiration in a sandy soil: comparison between eddy covariance measurements and estimates by the FAO 56 approach. Agricultural Water Management. 85: 305-313.

Parras Rosas, M. El plan de refuerzo de la competitividad del Conglomerado Agroindustrial Olivícola del Uruguay 2012-2020. https://www.gub.uy/ministerio-ganaderia-agricultura-pesca/sites/ministerio-ganaderia-agricultura-pesca/files/documentos/publicaciones/plan_conglomerado_olivicola_2012-2020.pdf Verficado junio de 2018

Pereira LS. 2004. Necessidades de Água e Métodos de Rega, Publicações Europa-América, Lisboa. Portugal. pp 312.

Pôças I, Paço TA, Paredes P, Cunha, M, Pereira LS. 2015. Estimation of actual crop coefficients using remotely sensed vegetation indices and soil water balance modelled data. Remote Sensing. 7(3): 2373-2400. doi:10.3390/rs70302373

Puppo L, García Petillo M. 2010. Determinación del consumo de agua del duraznero por lisimetría. Revista Brasileira de Engenharia Agrícola e Ambiental. ISSN 1415-4366, 14(1): 25-31.

Rapoport HF. 2008. Botánica y morfología. En: Barranco D, Fernández-Escobar R, Rallo L. (Eds.). El cultivo del olivo. Barcelona, España. Ediciones Mundi-Prensa, pp 36-62.

Searles PS, Saravia DA, Rousseaux MC. 2009. Root lenght density and soil water distribution in drip-irrigated olive orchards in Argentina under arid conditions. Acta Horticulturae. 949: 231-236.

Servili M, Esposto S, Lodolini E, Selvaggini R, Taticchi A, Urbani A, Montedoro S, Serravalle M, Gucci R. 2007. Irrigation effects on quality, phenolic composition and selected volatiles of virgin olive oil cv. Leccina. Journal of Agricultural and Food Chemistry. 55: 6609-6618.

Stevenson DS. 1989. Irrigation subsurface return flows and water use in lysimeter containing apple trees. Canadian Journal of Soil Science. 69: 769-778.

Testi L, Villalobos FJ, Orgaz F, Fereres E. 2006. Water requirements of olive orchards: I simulation of daily evapotranspiration for scenario analysis. Irrigation Science. 24: 69-76.

Testi L, Villalobos FJ, Orgaz F. 2004. Evapotranspiration of a young irrigated olive orchard in southern Spain. Agricultural and Forest Meteorology. 121: 1-18.

Tommasino H. Fortalecimiento de la cadena olivícola uruguaya. 2012. http://www2.mgap.gub.uy/OpypaPublicaciones/ANUARIOS/Anuario2012/material/pdf/13.pdf. Verificado junio de 2018.

Villalobos FJ, Orgaz F, Testi L, Fereres E. 2000. Measurement and modeling of evapotranspiration of olive (*Olea europea* L.) orchards. European Journal of Agronomy. 13: 155-163.

Villalobos FJ, Testi L, Orgaz F, García-Tejera O, Lopez-Bernal A, González-Dugo MV, Ballester-Lurbe C., Castel JR, Alarcón-Cabañero JJ, Nicolás-Nicolás E, Girona J, Marsal J, Fereres E. 2013. Modelling canopy conductance and transpiration of fruit trees in Mediterranean areas: A simplified approach. Agricultural and Forest Meteorology. 171-172: 93-103.

Wright JL. 1982. New evapotranspiration crop coefficients. Journal of the Irrigation and Drainage Division. 108(1): 57-74.