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4 **Modelling canopy conductance and transpiration of**  
5 **fruit trees in Mediterranean areas: a simplified**  
6 **approach**

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21 Abstract

22 Improving current approaches to quantify the transpiration of fruit trees is needed for water  
23 allocation purposes and to enhance the precision of water applications under full and deficit  
24 irrigation. Given that transpiration of tree crops is mainly modulated by canopy  
25 conductance ( $G_c$ ) and vapour pressure deficits, we developed a functional model of tree  
26 transpiration by quantifying an average daily  $G_c$  based on radiation use efficiency and  $CO_2$   
27 assimilation. For model calibration, an extensive experimental dataset of tree transpiration  
28 ( $E_p$ ) was collected in many of the main temperate fruit tree species, namely, apricot, apple,  
29 citrus, olive, peach, pistachio, and walnut, all under non-limiting water conditions, in  
30 different orchards in Spain and California (USA). In all species,  $E_p$  was assessed by  
31 measuring sap flux with the Compensation Heat Pulse method for several months, and a  
32 transpiration coefficient ( $K_t$ ) was calculated as the ratio of measured  $E_p$  to the reference  
33 evapotranspiration. For three deciduous species (apricot, peach and walnut)  $K_t$  showed  
34 maximum values close to 1, a value which stayed more or less constant throughout the  
35 summer in peach and walnut. The maximum  $K_t$  values were measured in pistachio (1.14)  
36 while they only reached 0.35 in olive and citrus trees. In the latter two species,  $K_t$  varied  
37 seasonally between 0.2 and 0.6 depending on the weather. The average  $G_c$  in July was high  
38 for apple, walnut, peach and pistachio (range 0.240-0.365 mol m<sup>-2</sup> s<sup>-1</sup>) and low for olive and  
39 orange (range 0.074-0.100 mol m<sup>-2</sup> s<sup>-1</sup>). The calibrated model outputs were compared  
40 against measured  $E_p$  data, suggesting the satisfactory performance of a functional model for  
41  $E_p$  calculation that should improve the precision of current empirical approaches followed  
42 to compute fruit tree water requirements.

43

## 44 **1. Introduction**

45 The estimation of evapotranspiration (ET) and its components (evaporation from the soil  
46 surface,  $E_s$  and transpiration or plant evaporation,  $E_p$ ) has been a key issue in hydrological  
47 studies (Nakayama, 2010; Wagner et al., 2011) and for improving irrigation management of  
48 agricultural crops (Evans and Sadler, 2008).

49 The most widely adopted method in agricultural water management for calculating ET is  
50 the one originally proposed by FAO (Doorenbos and Pruitt, 1977) that uses the product of  
51 two factors, the reference ET ( $ET_0$ ) that models the ET of an hypothetical grass surface and  
52 a crop coefficient ( $K_c$ ) that is proportional to crop ground cover and frequency of soil  
53 wetting. This method was later refined by Allen et al. (1998) through the development of a  
54 dual approach - crop coefficient, which separated  $K_c$  into a “basal” (crop) and a soil  
55 component - that *grosso modo* corresponds to separating  $E_p$  and  $E_s$ . However, in this case  
56 the basal crop coefficient includes  $E_p$  and some  $E_s$  when the soil is dry, which makes it  
57 almost impossible to check the validity of ET partitioning. The dual approach of Allen et al.  
58 (1998), was based on the original work of Wright (1982), which may be valid as an  
59 approximate engineering approach for ET estimation, but that may not be precise enough in  
60 many situations. Furthermore, the precise quantification of  $E_p$  is also important as it is  
61 related to canopy performance in terms of assimilation, and thus, productivity (Tanner and  
62 Sinclair, 1983). Also, evaluation of alternatives for water savings based on  
63 reduction/suppression of  $E_s$ , - an important issue that demands critical evaluation (Perry et  
64 al., 2009) and that is currently a subject of debate (Gleick et al., 2011) - depends on our  
65 ability to estimate  $E_p$ .

66 Fruit trees are usually irrigated in the arid and semi-arid areas and represent a large demand  
67 for irrigation water, which is rising given the increasing world demand for fruits and the  
68 high water productivity of perennials as compared to that of many annual crops. On the  
69 other hand, the large investments required and high production costs make the optimal use  
70 of water critical for the sustainability of commercial orchards. In this case a precise  
71 estimation of transpiration under non limiting conditions is required to set the upper limit of  
72 irrigation requirements, and to adjust it to assess the opportunities of reducing transpiration  
73 via deficit irrigation (DI; Fereres and Soriano, 2007). In recent years the literature on DI  
74 has been abundant, although in many studies a given DI program is compared to the  
75 commercial practice, but the actual differences in  $E_p$  between treatments are not assessed,  
76 precluding the estimation of transpiration reductions as compared to its maximum  
77 unstressed values (Lampinen et al., 2001; Ortuño et al., 2009; Pérez-Pastor et al., 2009).  
78 This clearly limits the applicability of many of these studies to conditions different from  
79 those of the original experiment.

80 The ET of fruit trees presents two distinct features as compared to that of annual crops; one  
81 is the large fraction of soil evaporation due to an incomplete ground cover that changes  
82 with plantation age and may be highly variable among orchards, but that seldom reach  
83 complete cover due to traffic and orchard management needs. The second is the tighter  
84 coupling of fruit tree canopies to the atmosphere due to the large roughness (Villalobos et  
85 al., 2000). The latter implies that transpiration will be mainly modulated by canopy  
86 conductance and vapour pressure deficit as opposed to short crops (including the reference  
87 grass surface), where transpiration is mostly dependent on solar radiation (Jarvis, 1985).  
88 Transferability of standard crop coefficients for fruit trees among different environmental

89 and orchard management conditions is thus open to some question, and alternative  
90 approaches to quantify orchard ET need to be sought.

91 Models of transpiration have been developed for many species with a wide variation of  
92 physiological detail (e.g. Dekker et al., 2000, for a basic review). In general they are based  
93 on the calculation of canopy conductance which is often done by applying empirical  
94 models of leaf conductance (e.g. Jarvis, 1976) to canopies (Stewart, 1988). Another  
95 approach links leaf conductance to CO<sub>2</sub> assimilation using semi-empirical equations (e.g.  
96 Ball et al., 1987; Leuning, 1995). Overall, the complexity of many assimilation models  
97 (e.g. Farquhar et al., 1980) needed to calculate conductance preclude the wide use of  
98 approaches linking conductance to assimilation outside the academic environment.

99 In an attempt to simplify the requirements of the more complex models, Orgaz et al. (2007)  
100 proposed a synthetic approach for assessing the canopy conductance of olive trees based on  
101 the concept of Radiation-Use Efficiency (Monteith, 1977; Anderson et al., 2000) as a  
102 surrogate for the assimilation model. This simplified approach has been tested successfully  
103 for olives in different environments and cultivars (Rousseaux et al., 2009; Fernandes-Silva  
104 et al., 2010; Martínez-Cob and Faci, 2010; Martín-Vertedor et al., 2011), and thus could  
105 serve as the basis for empirical models in other fruit tree species.

106 The development of transpiration or canopy conductance models has been hindered by the  
107 lack of accurate, long-term transpiration data at the orchard scale. The measurement of  
108 transpiration can be performed by few methods, for example gas exchange chambers or  
109 bags (Dragoni et al., 2005; Pérez-Priego et al., 2010), but in trees it is often based on  
110 determining sap velocity using heat as a tracer. Among the different methods available for

111 measuring sap flow the most common approach has been the heat dissipation technique  
112 (Granier, 1985) although recent studies indicate large potential errors depending on xylem  
113 thermal characteristics and tree size (Sevanto et al., 2009; Wullschleger et al., 2011). The  
114 Compensation Heat Pulse (CHP) method has been used successfully on many species  
115 (Swanson and Whitfield, 1981; Green et al., 2003), and it has shown better performance  
116 than other sap-flow methods (Steppe et al., 2010). A recent improvement in the  
117 methodology has overcome the problem of measuring low sap velocities with the CHP  
118 method (Testi and Villalobos, 2009). Records of sap velocity of different fruit tree species  
119 under a variety of conditions, are a prerequisite for the estimation of transpiration with  
120 sufficient accuracy as an input needed for the parameterization and experimental validation  
121 of transpiration models.

122 The objective of this study was to develop a generalized, simple transpiration model by: a)  
123 collecting a comprehensive transpiration data set using the CHP method in orchards of the  
124 main fruit tree species, namely olive, citrus, peach, apple, pear, apricot, pistachio and  
125 walnut; and, b) calibrating the conductance model of Orgaz et al. (2007) for the different  
126 species. This model is explicitly oriented to the calculation of tree crop water requirements  
127 for irrigation management, thus it was designed with functionality and low input  
128 requirements as its main features.

129

## 130 **2. Materials and methods**

131

### 132 **2.1. Canopy conductance model**

133

134 Starting with the leaf conductance model proposed by Ball, Woodrow and Berry (1987) and  
135 Leuning (1995), that established the linear dependence of conductance on CO<sub>2</sub> assimilation  
136 (A), Orgaz et al. (2007) calculated canopy conductance ( $G_c$ ) for olive trees as a function of  
137 tree intercepted radiation and vapour pressure deficit. This is based on the concept that  
138 canopy assimilation is proportional to radiation interception (Monteith, 1977) which was  
139 also underlying the foundation of the model of Anderson and Norman (Anderson et al.,  
140 2000). Here, we calculate canopy conductance for water vapour ( $G_c$ , mol m<sup>-2</sup> s<sup>-1</sup>) as:

141

$$142 \quad G_c = 1.6 c \frac{\alpha Q R_{sp}}{\left(1 + \frac{D}{D_0}\right) C_s} \quad (1)$$

143 where  $c$  is an empirical coefficient (dimensionless),  $\alpha$  is the radiation use efficiency ( $\mu\text{mol}$   
144  $\text{CO}_2 \mu\text{mol}^{-1}$ ),  $Q$  is the fraction of Photosynthetically Active Radiation (PAR) intercepted by  
145 the canopy (dimensionless),  $R_{sp}$  is the average incident daily PAR ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ),  $D$  is  
146 vapour pressure deficit (kPa),  $D_0$  (kPa) is an empirical coefficient related to the response of  
147 stomatal closure to  $D$ ,  $C_s$  is the CO<sub>2</sub> concentration in the leaf boundary layer ( $\mu\text{mol mol}^{-1}$ )  
148 and the coefficient 1.6 converts conductance for CO<sub>2</sub> to that of water vapour. Incorporating  
149 eq. 1 in the “imposed “ evaporation equation (Tan et al., 1978; McNaughton and Jarvis,  
150 1983) leads to the following equation to calculate the average transpiration rate during the  
151 daytime ( $E_p$ , mol m<sup>-2</sup> s<sup>-1</sup>):

152

153 
$$E_p = 1.6 c \frac{\alpha Q R_{sp}}{\left(1 + \frac{D}{D_0}\right) C_s} \frac{D}{P_a} \quad (2)$$

154 where  $P_a$  is atmospheric pressure (kPa).

155

156 Equation 1 might be re-arranged as follows:

157

158 
$$\frac{Q R_{sp}}{G_c} = \frac{C_s}{1.6 c \alpha D_0} (D + D_0) = a + b D \quad (3)$$

159 This equation indicates that if  $C_s$  and  $\alpha$  are constant, the ratio of intercepted radiation and

160 canopy conductance should be a linear function of  $D$  with an intercept of:  $a = C_s 1.6^{-1} c^{-1} \alpha^{-1}$

161 which depends on radiation use efficiency, and a slope of  $b = C_s 1.6^{-1} c^{-1} \alpha^{-1} D_0^{-1}$  which also

162 depends on the parameter for response to  $D$ .

163 Finally, for practical purposes, daily transpiration ( $E_{pd}$ , mm d<sup>-1</sup>) is expressed as a function

164 of total daily solar radiation ( $R_{sd}$ , MJ m<sup>-2</sup> d<sup>-1</sup>) as :

165 
$$E_{pd} = 37.08 \cdot 10^{-3} \frac{Q R_{sd}}{a + b D} \frac{D}{P} \quad (4)$$

166 where the coefficient  $37.08 \cdot 10^{-3}$  incorporates the conversion of units for Joules of solar

167 radiation to  $\mu\text{mol}$  quanta and from mol to kg of H<sub>2</sub>O, and  $a$  and  $b$  are the coefficients of the

168 linear function relating  $Q R_{sd} / G_c$  to  $D$  described above .



169 The model was calibrated by regressing for each experimental dataset the observed values  
170 of  $QR_{sd} / G_c$  on  $D$ . Daytime mean values of conductance were calculated by inversion of the  
171 imposed evaporation equation:

$$172 \quad G_c = \frac{E_p P_a}{D} \quad (5)$$

173 Where mean daytime values of transpiration were obtained by dividing total transpiration  
174 by day length and  $D$  was averaged for the daytime period.

175 Radiation interception was computed using the model of Mariscal et al. (2000) which is a  
176 version of the model of Norman and Welles of ellipsoids (Norman and Welles, 1983). In  
177 one experiment (apple) radiation interception was measured using ceptometers at 2-week  
178 intervals (Girona et al., 2011). For the other species the G-functions (ratio of projected area  
179 on leaf area) of foliage elements were calibrated as follows:

180 a) Orange and peach: using the leaf angle distributions measured in the same orchards of  
181 experiments Cs1 and Pp (Guillen-Climent et al., 2012). Values for apricot were assumed to  
182 be equal to those of peach.

183 b) Walnut: From measurements of transmissivity and canopy dimensions using a  
184 ceptometer (SunScan Canopy Analysis System, Delta-T Devices Ltd, Cambridge, UK) at  
185 different times of day during June 2009.

186 c) Pistachio: From measurements of transmittance of diffuse radiation performed using a  
187 Plant Canopy Analyzer (model LiCor LAI-2000, Lincoln, Ne, USA)

188 Values of leaf transmittance and reflectance were taken from Guillen-Climent et al. (2012)  
189 for orange and peach and from Ustin et al. (2009) for walnut. Values for apricot were  
190 assumed equal to those of peach and those of walnut were also used for pistachio.

191 In any case, for high values of LAI as those in the present study, the daily intercepted  
192 radiation is quite insensitive to the parameters related to leaf inclination, leaf transmittance,  
193 leaf reflectance or within-crown variations in leaf area density (Villalobos et al., 1995;  
194 Mariscal et al., 2000).

195 The days with rainfall were excluded from the analysis in all experiments, as in wet  
196 canopies sap flow is reduced substantially and most evaporation occurs directly from the  
197 wet surfaces.

198

199

## 200 2.2. Field experiments

201

202 In all the field experiments listed below tree transpiration was measured with a sap-flow  
203 system device developed and assembled at the IAS in Cordoba and described in Testi and  
204 Villalobos (2009). The system uses the Compensation Heat Pulse (CHP) method plus the  
205 Calibrated Average Gradient (CAG) technique (Testi and Villalobos, 2009); the latter is  
206 used when sap velocities lower than  $12 \text{ cm h}^{-1}$  prevent the use of the former method, or  
207 reduces its accuracy. The probes measure the heat pulse velocity at 4 depths in the xylem,  
208 spaced 10 mm; in all the experiments they were installed at an appropriate depth to measure

209 at 5, 15, 25 and 35 mm depth from the cambium. A full measurement cycle was performed  
210 every 15-min. The values of heat pulse velocity were then corrected for wounding effects  
211 (Swanson and Whitfield, 1981) assuming a 2.6 mm wound diameter for all the species  
212 considered, then converted to sap velocity and integrated first along the trunk radius (using  
213 the radial velocity profile curve given by the probe) and then around the azimuth angle  
214 (Green et al., 2003). The resultant sap flux is considered equivalent to the transpiration of  
215 the single tree.

216 Eight experiments (Table 1) were conducted to calibrate the transpiration model, with  
217 seven tree crops species of very different characteristics including fruit and nut crops, both  
218 evergreen and deciduous. These species represent approximately 30% of the land area of  
219 tree crops in the world, and more than 50% in Europe (FAOSTAT, 2010). All the  
220 experiments were conducted in Spain except Pv (Pistachio) which was carried out in  
221 California, USA. The code names used in Table 1 will henceforth be used to identify the  
222 different experiments.

- 223 • (Cs1.) This experiment was carried out in a 0.56 ha commercial citrus plot, (cultivar  
224 “Lane Late” orange) located in Alcalá de Guadaira, Seville, southern Spain. The plot  
225 was planted in 1997 and was drip irrigated. Two trees, irrigated to exceed the full water  
226 requirements, were instrumented with two sap flow probes per tree. Measurements  
227 started on 14/03/2008, and lasted until 19/11/2008. The meteorological variables were  
228 collected in an automated weather station located at 20 km distance.
- 229 • (Cs2.) A 1.7 ha plot of orange trees (cultivar “Lane Late”) planted in 2000, located in  
230 Chulilla, near the coast of Valencia, eastern Spain, was selected for measurements of  
231 transpiration in this experiment. The trees, 2.3m tall at the time of the experiment, were

232 surface irrigated until 2006, then drip irrigated since 2007. Two sap flow probes were  
233 inserted in the trunk of two trees, which were fully irrigated to avoid water stress.  
234 Measurements started on 13/02/2010, and lasted until 31/12/2010. An automated  
235 weather station placed 4 km from the plot provided standard meteorological data. More  
236 information about this plot is given in Ballester et al. (2012).

237 • (Jr.) Two 7-year walnut trees were instrumented with 4 sap-flow probes each, spaced  
238 90° along the trunk perimeter. The walnut trees in this 2.4 ha commercial plantation  
239 near Cordoba, Spain, were 6-7 m tall, drip irrigated without water restrictions.  
240 Measurements started on 20/3/2009 and ended on 25/11/2009. The meteorological  
241 measurements were taken in an automated weather station at 800-m distance from the  
242 plot.

243 • (Md.) The three apple trees of this experiment were planted in 1999 in a weighing  
244 lysimeter, installed inside a plot located in the IRTA experimental station, Lleida,  
245 north-eastern Spain. Two trees were instrumented with 2 probes each, while another  
246 one bore 4 probes. Trees were trained to a modified central-leader system, were 3.6 m  
247 tall and drip irrigated. Measurements of sap flow started on 28/5/2008 and lasted until  
248 18/9/2008. Meteorological data were registered with an automated weather station 20 m  
249 away from the orchard. More information on the plot can be found in Girona et al.  
250 (2011).

251 • (Oe.) This experiment was carried out in the research farm “Alameda del Obispo”,  
252 IFAPA, Cordoba, Spain. The trees of this 4 ha plot were planted in 1997 and were  
253 about 3.5 m tall, trained in free-shape as usual in this species. Four olive trees were  
254 instrumented, each one with two sap flow probes; the trees were drip irrigated, with an

255 amount that avoided water restrictions anytime during the season; the measurements  
256 were conducted throughout 2008 without interruption. The meteorological  
257 measurements were taken in an automated weather station at 300-m distance from the  
258 plot. More information on the orchard can be found in Iniesta et al. (2009)

259 • (Pa.) This experiment took place in a 1-ha plot of drip irrigated apricot trees in a  
260 commercial farm located in the Mula Valley near Murcia (South-eastern Spain). Two  
261 trees were monitored for transpiration by installing 4 sap flow probes to each tree. Trees  
262 were 10-years old, and had an average canopy height of 3.9 m. Measurements of sap  
263 flow started on 24/01/2009 and lasted until 31/12/2009. More information on this  
264 apricot plot can be found in Nicolas et al. (2005). An automated weather station in the  
265 same farm collected the meteorological data.

266 • (Pp.) Peach trees in this experiment were located in a commercial mature plantation of  
267 a clingstone type (cultivar “BabyGold 8”), which is typically fresh-marketed in Spain.  
268 Trees were 15 years old, vase-trained and drip irrigated. Two trees were fitted with 4  
269 sap-flow probes each, spaced 90°; these trees and the adjacent neighbours were irrigated  
270 in excess to ensure avoidance of water stress throughout the season. Measurements  
271 started on 21/3/2008 and ended on 25/11/2008; trees were harvested at mid July. The  
272 meteorological measurements were taken in an automated weather station at 1000-m  
273 distance from the plot.

274 • (Pv.) This experiment took place in a commercial farm located in Madera County,  
275 California, USA. The pistachio trees in this 32 ha plot were planted in 1994; they were  
276 3.8 m tall, and fully irrigated with below-canopy sprinklers that wetted completely the  
277 soil surface. The meteorological measurements were taken in an automated weather

278 station at 13 km distance from the plot. Measurements of sap flow started on 20 May  
279 2006 and lasted until 1 October 2006. More information on this orchard can be found in  
280 Testi et al. (2008) and Iniesta et al. (2008)

281 In all the experiments, the transpiration at the stand scale ( $\text{mm day}^{-1}$ ) was obtained by  
282 dividing the tree transpiration (obtained via sap flux measurements) by the area of the  
283 planting pattern, after verifying that the canopy size of the instrumented trees was  
284 representative of the average canopy in the stand.

285 The reference evapotranspiration ( $ET_0$ ) was calculated following the standard Penman-  
286 Monteith - FAO method (Allen et al., 1998) for all experimental sites. The transpiration  
287 coefficient ( $K_t$ ) was calculated as the ratio between the stand transpiration and the  $ET_0$ .

288

### 289 **3. Results**

290

#### 291 3.1. Environmental conditions

292 All the experiments were performed in locations with a Mediterranean-type climate, where  
293 conditions of little or no rainfall and high evaporative demand concur during summer.

294 Daytime mean air temperature was between 25.6 and 31.5°C for the different experiments  
295 (Table 2) while vapour pressure deficit (daytime) was in the range of 2.7-3.3 kPa with the  
296 exception of Lleida (2008) and Valencia that showed the most humid conditions ( $D=1.4$   
297 kPa and 1.9 kPa, respectively). The average  $ET_0$  was lowest for Lleida (2008) ( $4.0 \text{ mm d}^{-1}$ )

298 and highest for Seville (2008) ( $6.2 \text{ mm d}^{-1}$ ). Total rainfall during the summer exceeded 40  
299 mm in Lleida (57.4 mm in 2008), and Mula (67.5 mm in 2009) (Table 2).

300

301

### 302 3.2. Transpiration and transpiration coefficients

303

304 Transpiration rates were highly variable among sites and through the year (Fig. 1) usually  
305 increasing from spring to summer and then decreasing again in autumn. Maximum  
306 transpiration was observed in all cases around 1 July with the exception of apple, where  
307 insufficient data does not allow a clear assessment of the seasonal transpiration trends.

308 Maximum values in the summer were above  $7 \text{ mm d}^{-1}$  for walnut (Jr), peach (Pp) and  
309 pistachio (Pv). Lower values were observed for olive (Oe) and orange (Cs1 and Cs2, 2-2.5  
310  $\text{mm d}^{-1}$ ) while intermediate values were found for apple (Md,  $5 \text{ mm d}^{-1}$ ) and apricot (Pa, 3.7  
311  $\text{mm d}^{-1}$ ).

312 The transpiration coefficient  $K_t$  exhibited different patterns (Fig. 2). For the three deciduous  
313 species for which we had data for the whole growing season (apricot, peach and walnut) the  
314  $K_t$  showed maximum values close to 1. For peach and walnut the  $K_t$  increased up to a  
315 maximum at the end of May, then stayed around the maximum value with small variations  
316 throughout the summer, and then decreased in autumn until leaf fall. This final reduction  
317 was rapid in peach and apricot (2-3 weeks) and slower in walnut, where the  $K_t$  started to  
318 decrease already in September. Apricot presented also maximum values of the transpiration

319 coefficient during the fall, similar to peach. Unfortunately the insufficient data in apple  
320 only allows the comparison of values at the start (mean  $K_t = 1.03$ ) and at the end of summer  
321 (mean  $K_t = 0.87$ ). Pistachio showed an overall mean  $K_t$  of 1.19 with occasional values  
322 around 1.4; leaf appearance and fall were outside the measurement period in this  
323 experiment.

324 In olive the transpiration coefficient during summer was around 0.35 and showed a marked  
325 increase from DOY 220 onwards. The variability was higher during spring with values  
326 below 0.2 in the period from DOY 85 to 92.

327 Oranges in Valencia (Cs2) showed a  $K_t$  during summer of 0.30-0.35 which tended to  
328 increase and had greater variability in autumn. Lower values were observed in spring (DOY  
329 70 to 100). In Alcalá de Guadaira oranges (Cs1) a similar behaviour, with values of  $K_t$   
330 between 0.3 and 0.4 in spring and summer and between 0.4 and 0.6 in autumn, was  
331 observed.

332

333

### 334 3.3. Canopy conductance

335

336 The bulk canopy conductance ( $G_c$ ) was highly variable among experiments and through the  
337 year (Fig. 3), usually decreasing from spring to summer and then increasing again in the  
338 autumn. The average  $G_c$  in July (DOY 180-210 approx) was high for apple, walnut, peach  
339 and pistachio (range 0.240-0.365 mol m<sup>-2</sup> s<sup>-1</sup>) and low for olive and orange (range 0.074-



340  $0.100 \text{ mol m}^{-2} \text{ s}^{-1}$ ).  $G_c$  peaked around DOY 150 (end of May) in many species: orange  
341 (especially Cs1), walnut, apricot and (some days earlier) in peach. Olive  $G_c$  also shows a  
342 less pronounced peak in this period. The datasets of apple and pistachio seem to follow the  
343 same behaviour although the data collection started too late to show it clearly. A second  
344 peak in  $G_c$  is apparent in autumn, especially in orange and olive, but also in the deciduous  
345 peach and apricot species.

346

347

#### 348 3.4. Model calibration and testing

349

350 The coefficients of the linear regression equations of  $(Q R_{sp})/G_c$  on  $D$  (Eq. 3) are presented  
351 in Table 3. The intercepts ranged from 333 (peach) to  $1287 \mu\text{E mol}^{-1}$  (walnut), while the  
352 slope values oscillated between 624 (pistachio) and  $2050 \mu\text{E mol}^{-1} \text{ kPa}^{-1}$  (apricot). The  
353 confidence intervals of the intercepts overlapped for peach, pistachio, apricot and apple on  
354 the one hand, and for olive, walnut and orange on the other hand. The slope intervals  
355 indicated a group of low values (peach, walnut and pistachio) and a group of high values  
356 (olive and orange) while apple showed an intermediate value. Table 3 presents also the  
357 RMSE (in  $\text{mm day}^{-1}$ ) of the results of comparing Equation 2 (with the given parameters) to  
358 the observed  $E_p$ .

359 The  $E_p$  output of Eq.2 has also been plotted over the measured data in Fig. 1, as a visual test  
360 of the goodness-of-fit. The visual appraisal of the calibrated model output in Fig. 1 suggests

361 the following observations. Firstly, in all the species and experiments the output of Eq. 2  
362 matches well the seasonal pattern without any clear period of over- or underestimation,  
363 suggesting that - in the climates where these experiments took place - this model accounts  
364 for the seasonal variability of transpiration. As a corollary, the RMSE of Table 3 does not  
365 seem to be biased in any part of the irrigation season, which implies that the capacity of Eq.  
366 2 of predicting transpiration will increase over periods longer than a day (irrigations  
367 amounts are often calculated at a weekly or a monthly basis). Second, the goodness-of-fit of  
368 Eq. 2 is very similar for all the different species, suggesting that the assumptions made in  
369 this model (for example those associated with the high coupling with the atmosphere) are of  
370 a general nature, and the physiological differences between species can be handled by  
371 calibration parameters. Last, it seems that short periods of low transpiration (associated to  
372 occasional cloudy days or in general transitory low evaporative demand) are sometimes  
373 cause of worse fit over the measured data. Some examples can be in Cs1 around DOY 250,  
374 in Md around DOY 150, or in Pa in the cloudy days ranging from DOY 255 to 290.  
375 Nevertheless a high responsiveness to humid conditions is present in other occasions, e.g.  
376 in Cs1 around DOY 100 or in CS2 around DOY 260.

377

#### 378 **4. Discussion**

379

380 In this study we have collected a large dataset of transpiration data of well irrigated fruit  
381 trees using the same methodology, the Compensation Heat Pulse, and we have analyzed the  
382 data using a simplified version of the equation of Leuning at the canopy scale. Technical

383 problems with the irrigation and/or with the measurement system limited the availability of  
384 data in apricot and apple relative to the amount of data collected in the other species where  
385 we were able to characterize transpiration for the whole irrigation season.

386 Table 4 presents a representative sample of the transpiration rates and transpiration  
387 coefficients that appeared in literature for some of the species studied here. A rational  
388 comparison of these values is not straightforward for several reasons. Most studies provide  
389 only a few days of measurement (e.g. Auzmendi et al., 2011). In some cases transpiration  
390 was limited by water deficit (e.g. Dragoni et al., 2005; Gong et al., 2006; Gong et al., 2007;  
391 Masmoudi et al., 2010) and only a few provide data of canopy size, Leaf Area Index (LAI)  
392 or intercepted radiation. Published values of maximum transpiration rates in the summer  
393 are in the range 2.96-7.45 mm d<sup>-1</sup> for apple, 1.25-1.65 mm d<sup>-1</sup> for apricot, 3.9-8.0 mm d<sup>-1</sup>  
394 for orange, 1.12-4.3 mm d<sup>-1</sup> for olive and 4-7 mm d<sup>-1</sup> for peach (Table 4). No published  
395 data of transpiration at the stand scale has been found for either walnut or pistachio.

396 The transpiration rates were more variable in spring and autumn, as weather conditions  
397 were also more variable (summer is often steadily hot and dry in the Mediterranean  
398 climates where the experiments took place). The presence of intercepted water on the  
399 foliage after rainfall events adds further variability. The large day to day variability in the  
400 transpiration coefficients casts doubts on their transferability to different climatic  
401 conditions confirming the observations of Dragoni et al. (2005).

402 Maximum transpiration rates for orange in summer were higher in Cs1 than in Cs2, but  
403 transpiration coefficients were almost the same. The differences are probably due to the  
404 higher evaporative demand of the Cs1 site (near Seville, inland southern Spain) from that of

405 Cs2 (near Valencia, eastern Spain, coastal region); the conductance model seems to capture  
406 the environmental differences, as the parameters for the two experiments were very close  
407 (Table 3). The similar behaviour of conductance for olive and orange confirms the  
408 preliminary results of Villalobos et al. (2009).

409 The sensitivity of canopy conductance to vapour pressure deficit in the model of Leuning  
410 (1995) is inversely proportional to parameter  $D_0$ , which is an output of the calibration of  
411 Eq.3 with our datasets. Walnut showed a value (1.91 kPa) clearly higher than those found  
412 in the other species (Table 3) which ranged between 0.49-0.84 kPa, with the exception of  
413 apricot (0.22 kPa). This low value of apricot should be taken with caution as the intercept  
414 was not significantly different from zero. A possible explanation could be that the dataset  
415 was restricted to the end of summer and beginning of autumn when changes in the  
416 physiology of leaves and a decline in their maximum stomatal conductance could explain  
417 the low value encountered.

418 The main advantages over the standard FAO method (Allen et al., 1998) of using this  
419 model of canopy conductance to calculate transpiration (Eq. 4) are a more mechanistic  
420 approach that increases the precision of the  $E_p$  estimate and the reduced data requirements  
421 (air temperature, vapour pressure deficit and solar radiation) relative to the FAO method  
422 that requires also wind speed. Solar radiation and vapour pressure deficit may also be  
423 estimated from maximum and minimum air temperature using the Hargreaves method  
424 (Hargreaves and Samani, 1985) for solar radiation and taking minimum temperature as a  
425 surrogate for dew point temperature. Additionally, the FAO crop coefficient approach  
426 assumes that the response of crop ET to weather variables is always the same. However, in  
427 a changing climate with increasing  $CO_2$  concentration we should expect a reduction in leaf

428 (and thus, canopy) conductance. The overall effect on the crop coefficient would depend on  
429 the coupling of the crop to the atmosphere as compared to grass which is a smooth  
430 uncoupled surface, unlike trees. By contrast, the model proposed here could account for the  
431 changes in canopy conductance by modifying the coefficients a and b of eq. 3 in proportion  
432 to atmospheric CO<sub>2</sub> concentration and expected changes in radiation use efficiency. Taub  
433 (2010), summarizing the results from free air CO<sub>2</sub> enrichment (FACE) experiments,  
434 indicated that the increase in CO<sub>2</sub> concentration to 475-600 ppm will increase aerial dry  
435 matter production of C3 crops by 17%. Taken an average future value of 540 ppm and  
436 using Eq. 1 we should expect a reduction in canopy conductance of 18%, which is close to  
437 the mean value observed in FACE experiments (22%). On the other hand the expected  
438 increase in vapour pressure deficit will depend on the increase in air temperature. By  
439 supposing a 2 K increase in the air temperatures of the experimental sites of Table 2, the  
440 vapour pressure deficit would raise between 0.4 and 0.6 kPa which represents a 15-20%  
441 increase, with the exception of Lleida, where it would be 30%. In any case, the combination  
442 of lower conductance (80% of actual) and higher vapour pressure deficit (115-130% of  
443 actual) leads to almost no change in the expected future transpiration rates (92-104% of  
444 current values). This estimate of future  $E_p$  contrasts with the expected increases of  
445 transpiration if one uses reference ET ( $ET_0$ ) and a constant  $K_t$ , as  $ET_0$  increases linearly  
446 with vapour pressure deficit. The latter calculations lead to an increase in evaporation from  
447 crops due to global warming which is widely accepted in the literature (e.g. Rodríguez Díaz  
448 et al., 2007). The overall picture of future tree crops transpiration is further complicated by  
449 a potential protraction of vegetative cycles in a warmer climate, thus any conclusion with  
450 the present datasets and model would be speculative. Nevertheless the model responds to

451 the main changes on the crop-climate binomial, thus is a step forward with respect to the  
452 simpler approaches currently used for the calculation of crop water requirements.

453 The model presented here predicts that the increase in transpiration slows down as vapour  
454 pressure deficit (D) increases. This implies that the transpiration coefficient should be  
455 higher for intermediate D and would decrease for either high or low values. This confirms  
456 the increase of  $K_t$  with D in a humid climate observed by Dragoni et al. (2005) in apple.

457 The fraction of intercepted radiation (Q) is required for the calculation of bulk canopy  
458 conductance. A summary model such as the one proposed by Orgaz et al (2007) allows the  
459 calculation of Q as a function a tree dimensions and planting density. Although calibrated  
460 for olive trees, the same approach should hold for other species provided that leaf area  
461 density is high enough. Additional studies are needed to determine if the same procedure  
462 describes adequately the value of Q for other species and orchard management approaches.

463 Pereira et al. (2006) proposed a simple model for calculating the transpiration of fruit trees  
464 as the product of LAI,  $ET_0$  and a coefficient which was reported to be the same for olive,  
465 apple, walnut and grapes. Therefore the  $K_t$  should be equal to the coefficient multiplied by  
466 LAI. The model is not only flawed because of the incorrect scaling up of radiation  
467 interception (Villalobos, 2008) but because it would predict the same transpiration for the  
468 different species if LAI is the same. This is obviously at odds with our observations. For  
469 instance, in 2008 peach showed a summer  $K_t$  above 1 with LAI 1.5 while orange in Seville,  
470 with a slightly higher LAI (1.7) had a  $K_t$  below 0.4. Another inconsistency of the model of  
471 Pereira et al (2006) is that if we increase the planting density with the same LAI (thus with  
472 more, smaller canopy units) we would increase intercepted radiation, and thus productivity

473 and transpiration. This is based on basic principles (Loomis and Connor, 1992) and has  
474 been confirmed by models and observations (e.g. Mariscal et al., 2000). LAI is thus not a  
475 good choice for scaling up transpiration in fruit trees, except for very low values, when  
476 intercepted radiation and LAI are linearly related.

477 The equations provided in Table 3 together with an assessment of intercepted radiation,  
478 allow the computation of transpiration in the main fruit tree species under different climates  
479 with a degree of precision that should be greater than the standard engineering  
480 methodology which uses a single crop coefficient regardless of climate.

481

482

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484

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494

495



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665

666 **Tables**

667

668 **Table 1.** List of sap flow experiments carried out to measure transpiration in different  
 669 species, with their main characteristics.  $ET_0$  = reference evapotranspiration.  $E_p$  =  
 670 transpiration. LAI = Leaf Area Index.

671

Code	Cs1	Cs2	Jr	Md	Oe	Pa	Pp	Pv
Species	<i>Citrus x sinensis</i> (Orange)	<i>Citrus x sinensis</i> (Orange)	<i>Juglans regia</i> (Walnut)	<i>Malus domestica</i> (Apple)	<i>Olea europaea</i> (Olive)	<i>Prunus armeniaca</i> (Apricot)	<i>Prunus persica</i> (Peach)	<i>Pistacia vera</i> (Pistachio)
Cultivar	Lane Late	Lane Late	Chandler	Golden Smoothee	Arbequina	Búlida	Baby Gold 6	Kerman
Location	Alcalá de Guadaira	Valencia	Cordoba	Lleida	Cordoba	Mula	Cordoba	Madera CA-USA
Lat (deg)	37.35	39.65	37.85	41.62	37.85	37.92	37.85	36.98
Long (deg)	-5.80	-0.88	-4.80	-0.89	-4.80	-1.42	-4.80	-119.96
Start	14-03-08	13-02-10	20-03-09	28-05-08	01-01-08	24-01-09	21-03-08	26-05-06
End	19-11-08	31-12-10	25-11-09	18-09-08	31-12-08	31-12-09	25-11-08	01-10-06
Duration (days)	251	322	251	114	366	311	250	135
Planting pattern (m)	7 x 3	6 x 4	8 x 8	4 x 1.6	7 x 3.5	8 x 6	5 x 3.25	5.8 x 5.2
Ground cover (n/d)	0.42	0.33	0.66	0.5	0.49	0.65	0.54	0.57
$ET_0$ (mm) *	914	1214	1067	446	1233	981	1064	832
Age (years)	11	10	7	9	11	10	15	12
Rainfall (mm) *	219	469	139	89	546	458	407	26
Irrigation (mm) *	586	430	1223	765	472	437	1100	760
$E_p$ (mm) *	431	353	960	522	446	580	1063	808
LAI (m <sup>2</sup> m <sup>-2</sup> ) **	1.7	1.1	2.8	2.5	1.1	1.9	1.5	1.9

672

673 \*: accumulated amounts in the experimental period

674 \*\*: maximum during the experimental period

675

676 **Table 2.** Weather conditions during summer (21 June to 20 September) for the different  
 677 experiments. Air temperature (T) and Vapour Pressure Deficit (D) are the averages for the  
 678 daytime period.

679

Location/year	Experiment	Total rainfall (mm)	rainy days (no.)	Average T (°C)	Average D (kPa)	Average ET <sub>0</sub> (mm day <sup>-1</sup> )
Lleida 2008	Md	57.4	16	25.6	1.4	4.0
Mula 2009	Pa	67.5	5	31.5	2.7	4.7
Valencia 2010	Cs2	34.3	12	26.8	1.9	5.2
Cordoba 2008	Pp, Oe	8.1	2	29.6	2.9	6.0
Seville 2008	Cs1	6	4	29.3	3.2	6.2
Cordoba 2009	Jr	20.1	4	29.8	3.0	5.8
Madera 2006	Pv	0.0	0	28.8	2.7	5.8

680



681 **Table 3.** Regressions of the ratio of intercepted radiation and canopy conductance versus  
 682 Vapour Pressure Deficit. The lower and upper limits for the parameters a and b correspond  
 683 to the confidence interval at a 95% probability level. The data did not include rainy days or  
 684 conditions of water deficit. The parameter  $D_0$  in the conductance model was calculated as  
 685 the ratio a/b (Eq. 3). The root mean square error (RMSE) of the simulated transpiration ( $E_p$   
 686 from Eq. 2) versus the observed one ( $\text{mm day}^{-1}$ ) is also presented.

687

Experiment	Species	a			b			$r^2$	n	$D_0$	RMSE
		$(\mu\text{E mol}^{-1})$			$(\mu\text{E mol}^{-1} \text{ kPa}^{-1})$						
		value	lower	upper	value	lower	upper				
Cs1	Orange	1070	701	1439	1566	1428	1703	0.75	173	0.68	0.35
Cs2	Orange	1002	732	1271	1666	1493	1838	0.77	115	0.60	0.21
Jr	Walnut	1287	970	1604	673	578	768	0.71	83	1.91	0.23
Md	Apple	442	267	617	911	775	1047	0.83	40	0.49	0.38
Oe	Olive	1211	866	1557	1447	1320	1575	0.83	104	0.84	0.32
Pa	Apricot	452	-279	1182	2050	1622	2479	0.64	53	0.22	0.34
Pp	Peach	333	222	444	633	594	673	0.90	120	0.50	0.62
Pv	Pistachio	359	220	498	624	569	679	0.82	123	0.58	0.67

688

689

690 **Table 4.** Values of maximum  $E_p$  for some fruit species and vegetation density in previous  
 691 experiments reported in the literature. Asterisks denote the potential occurrence of water  
 692 stress; n/d = non-dimensional; LAI= Leaf Area Index;  $E_p$ = transpiration;  $K_t$  = transpiration  
 693 coefficient ( $E_p/ET_0$ ).

Species	Source	Max $E_p$ (mm d <sup>-1</sup> )	$K_t$ (n/d)	Age (y)	Spacing (m or m <sup>2</sup> )	Leaf Area (m <sup>2</sup> )	LAI (m <sup>2</sup> m <sup>-2</sup> )	Ground cover (%)
Apple	Gong et al. (2007) (*)	5.9	-	8	3x3.2	-	3.2	60
	Gong et al. (2006) (*)	5.2	-	7	3x3.2	-	2.6	-
	Dragoni et al. (2005) (*)	4.8	-	8	4.28x1.83	14	1.8	-
	Li et al. (2002)	7.2	-	15	4.5x2	16.7	1.85	-
	Cohen et al. (2002)	7.45	-	16	4.5x2	16.7	1.85	-
	Auzmendi et al. (2011)	5	-	12	4X1.6	15.1	2.36	-
	Green et.al. (1999)	2.96	-	14	3x4.5	29.5	-	52
Apricot	Nicolás et al. (2005)	1.65	-	11	8x8	190	-	52
	Alarcón et al. (2003)	1.25	-	11	8x8	190	-	52
Orange	Rana et al. (2005)	8	-	10	5x5	-	2.5	-
	Yang et al. (2003)	3.9	-	8	1.5x1.5	-	-	35
Grapefruit	Cohen (1991)	4.16	-	17	5.7x4	-	5.5	80
Olive	Masmoudi et al. (2010) (*)	1.14	0.13	6	6x6	14	-	35
	Er-Raki et al. (2010)	4.3	-	240	45m2	-	3	-
	Rousseaux et al. (2009)	2.3	-	7	4x8	-	-	23
	Yunusa et al. (2008)	3.2	0.47	11	8x5	-	1.11	-
	Santos et al. (2007)	1.12	1	80	12x12	-	-	-
	Williams et al. (2004)	2.2	-	240	45m2	-	3	-
	Fernández et al. (2001)	2.1	0.32	29	7x5	-	-	-
Peach	Gonzalez-Altozano et al. (2008)	6	-	5	2x4	-	-	-
	Gong et al. (2005)	7	1.16	7	4x6	-	-	30
	Conejero et al. (2007)	4	0.8	5	5x5	-	-	54

695 **Figure 1.** Time series of daily transpiration rate ( $E_p$ ) estimated from sap flow  
696 measurements in the eight experiments (dots). The line is the  $E_p$  calculated from Eq. 2 with  
697 the optimised parameters of Table 3.

698 **Figure 2.** Time series of coefficient of transpiration  $K_t$  (the ratio of crop transpiration over  
699 reference evapotranspiration, or  $E_p / ET_0$ ) in the various experiments. The “wet” days with  
700 rainfall  $> 0.2$  mm were ignored, as both numerator and denominator tend to be lower than  
701 measurement errors, making  $K_t$  uncertain.

702 **Figure 3.** Time series of observed bulk canopy conductance, calculated by inverting the  
703 imposed evaporation equation.

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