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Bernard Mougenot

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1 **Evaluation and analysis of deep percolation losses of drip irrigated citrus**
2 **crops under non-saline and saline conditions in a semi-arid area**

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4 H., Nassah¹, S., Er-Raki^{2*}, S., Khabba³, Y., Fakir¹, F., Raibi⁵, O. Merlin⁴, B., Mougenot⁴

5

6 ¹GEOHYD, Département de Géologie, Faculté des Sciences Semlalia, Université Cadi Ayyad,
7 Marrakech, Morocco

8 ²LP2M2E, Département de Physique Appliquée, Faculté des Sciences et Techniques, Université Cadi
9 Ayyad, Marrakech, Morocco

10 ³LMME, Département de Physique, Faculté des Sciences Semlalia, Université Cadi Ayyad,
11 Marrakech, Morocco

12 ⁴CESBIO, Centre d'Etudes Spatiales de la Biosphère, Toulouse, France

13 ⁵CNESTEN, Centre National de l'Energie des Sciences et des Techniques Nucléaires, Morocco

14 *Corresponding author address:

15 Dr. Salah Er-Raki

16 LP2M2E, Département de physique, Faculté des Sciences et Techniques (FSTG), Cadi Ayyad
17 University. Av. Abdelkarim Elkhatabi. B.P 549, 40000 Marrakech, Morocco

18 Tel: (+212) (0) 524 43 34 04 / Fax: (+212) (0) 524 43 31 70

19 Email: s.erraki@uca.ma/s.erraki@gmail.com

20 **Abstract**

21 In arid and semi-arid regions, irrigation management is important to avoid water loss by soil
22 evaporation and deep percolation (DP). In this context, estimating the irrigation water demand
23 has been investigated by many studies in the Haouz plain. However, DP losses beneath
24 irrigated areas in the plain have not been quantified. To fill the gap, this study evaluated DP
25 over two drip-irrigated citrus orchards (Agafay and Saada) using both water balance and
26 direct fluxmeter measurement methods, and explored the simple FAO-56 approach to
27 optimise irrigation in order to both avoid crop water stress and reduce DP losses in case of
28 non-saline and saline soils. The experimental measurements determined different terms of the
29 water balance by using an Eddy-Covariance system, fluxmeter, soil moisture sensors and a
30 meteorological station. Using the water balance equation and fluxmeter measurements, results
31 showed that about 37% and 45% of supplied water was lost by DP in Saada and Agafay sites,
32 respectively. The main cause of DP losses was the mismatch between irrigation and the real
33 crop water requirement. For Agafay site, it was found that increased over-irrigation had the
34 effect of reducing soil salinity by leaching salts.

35 The applied FAO-56 model suggested an optimal irrigation scheduling by taking into account
36 both rainfall and soil salinity. The recommended irrigations could save about 39% of supplied
37 water in non-saline soil at Saada and from 30% to 47% in saline soil at Agafay.

38 Key words: Saline soil; water balance; fluxmeter; FAO-56 approach; irrigation scheduling.

39 **1. Introduction**

40 In the southern Mediterranean region, as in many arid and semi-arid regions of the world,
41 water scarcity is one of the main factors limiting crop development, growth and yield
42 (Kharrou et al., 2013). In this region, irrigation is a major component of water demand. It is
43 estimated that about 83% of available resources is dedicated to agriculture with an efficiency
44 lower than 50% (Chehbouni et al., 2008). In Morocco, this waste of water has several origins
45 including leakage during water routing, but also a lack of irrigation efficiency in the field
46 (Khabba et al., 2013; Belaqziz et al., 2014). Indeed, scheduling in timing and amount of
47 irrigation is mostly determined according to the water availability so that the actual plant
48 water needs are generally not taken into account. In addition, the traditional flooding systems
49 are predominantly leading to significant water loss by soil evaporation and deep percolation
50 (DP) (Kharrou et al., 2011). Currently, the Moroccan government has set up an ambitious

51 program for irrigation conversion from flood to drip (PMV, 2013). However, the obtained
52 results for DP are surprising as an inadequate use of the drip technique may lead to substantial
53 water losses (Khabba et al., 2013). It has been shown that the DP losses for the drip irrigation
54 sites are in the range 29-41 % of water input while they are relatively lower for flood
55 irrigation, ranging from 26 to 31 % (Khabba et al., 2013). Moreover, as the soil salinity may
56 limits plant growth (Ayars et al., 2012), the farmers usually apply excessive irrigation to leach
57 soil salinity out of root layer or root zone and hence avoid salinity stress (Visconti et al.,
58 2012). In general, over-irrigation amounts are arbitrary and largely estimated. In our study
59 basin, this situation leads to an overexploitation of groundwater, with a level decreasing from
60 1 to 3 m year⁻¹ (Le Page et al., 2012; Boukhari et al., 2015).

61 In order to preserve water resources, the rationalisation of irrigation water use is necessary.

62 An accurate estimation of the water consumed by evapotranspiration (ET) and lost by DP
63 would provide a basis for improving irrigation efficiency (Kharrou et al., 2013; Belaqziz et
64 al., 2014; Xianwen et al., 2016).

65 Regarding ET, crop coefficients and associated measurements have been reported in the
66 literature and used to test, develop and calibrate a range of ET models (Allen et al., 2011; Er-
67 Raki et al., 2013). DP is commonly assessed by the soil water balance equation when both ET
68 and water supply irrigation and rainfall are available (Sammis et al., 1983). The method has
69 been used under different irrigation techniques and for various crops (Vázquez et al., 2006;
70 Wang et al., 2012). DP can also be measured by direct methods such as lysimeters (Allen et
71 al., 1991; Kim et al., 2011; Duncan et al., 2016), or fluxmeters (Deurer et al., 2008; Gee et al,
72 2009). However, these methods are expensive (Upreti et al., 2015) and may disrupt flow,
73 causing errors in the measured drainage (Gee et al., 2009).

74 Other indirect methods have also been used such as the hydraulic method (Qinbo et al., 2011;
75 Allman et al., 2015), temperature measurements in the unsaturated zone (Constantz et al.,
76 2003; Landon et al., 2016), and geochemical tracers (Stonestrom et al., 2003; Stephens et al.,
77 2006).

78 In Morocco, citrus is one of the main components of agricultural systems (Boubker, 2004).
79 Currently, it covers a total area of about 120,000 ha (MAPM, 2013), but it is in rapidly
80 expanding. However, in Morocco, the key physiological stages of this crop (from flowering to
81 maturation) coincide with the dry period (March-October). Thus, intensive irrigation is
82 necessary for citrus development (El Hari et al., 2010). As far as we know such a study on the
83 estimation of DP for citrus in Morocco conditions has never been performed before.

84 In this context, the objective of this study is twofold: 1) the evaluation and analysis of DP for
85 citrus orchards irrigated by drip system and grown under semi-arid conditions, and 2) the
86 exploration of FAO-56 simple approach to optimise irrigation in order to both control crop
87 water stress and to reduce DP in the case of saline and non-saline soils. The analysis of DP
88 losses can potentially provide useful information for optimising citrus irrigation schedules
89 under non-saline and saline soil conditions. To our best knowledge it is the first time that the
90 FAO-56 method has been tested for citrus under saline soil conditions.

91 **2. MATERIALS AND METHODS**

92 **2.1. Sites description**

93 The study was conducted on two citrus orchards: Agafay and Saada (Figure 1). The Agafay
94 site covers an area of 38 ha approximately 44 km southwest of Marrakech city (31°29'
95 50.19"N, 008°25' 02"W). The field experiment was carried out from 2006 to 2013 in a
96 mandarin orchard planted in July 2000. The trees were planted at a spacing of 4 m in rows and
97 6 m between rows, which is about 35% ground cover. The height of trees was about 3 m and
98 the depth of the root zone around 0.6 m. This depth was determined by making five pits near
99 to the tree's root zone. The crop was maintained in over-irrigated conditions by drip irrigation:
100 the irrigation frequency was almost every day without taking into account rainfall events.
101 Moreover, the amount of water applied by the farmers during each irrigation event varied
102 between 2 and 9 mm day⁻¹ depending on climatic conditions. The Agafay site is divided into
103 three sectors and irrigated within 24 hours at a rate varying from 28 to 60 m³ ha⁻¹. Note that
104 irrigation is applied during rainfall events in order to leach the soil salinity from the root zone.

105 The soil type is homogeneous, with high sand and low clay contents (18% clay, 32% silt and
106 50% sand). According to the pedo-transfer function of Wosten et al. (1997) the soil moisture
107 at field capacity (θ_{fc}) and wilting point (θ_{wp}) are 0.26 and 0.12 mm³ mm⁻³, which corresponds
108 to 156 and 72 mm at the root zone at the experimental plot, respectively.

109 The Saada site is located approximately 15 km west of Marrakech city (31°37'36''N,
110 08°09'35''W). It covers an area of 128 ha and is planted with 13-year old mandarin trees; the
111 field experiment was conducted during 2004. The orange trees were placed at a spacing of 5
112 m in rows and 3 m between rows, with 70% of the ground cover fraction. The average height
113 of the trees was about 3.15 m and the depth of the root zone was about 0.6 m. The Saada
114 citrus was maintained in over-irrigated conditions by daily irrigation varied from 2 to 5 mm,
115 depending on climatic conditions. The orchard is divided into several sectors, but all irrigated
116 on the same day with a rate varying from 4 to 56 m³ ha⁻¹. The soils have high sand and low

117 clay contents (12% clay, 38% silt, and 50% sand). More details about the two sites can be
118 found in the studies by Er-Raki et al. (2009) and Er-Raki et al. (2012).

119 For both sites, the farmers use the reference evapotranspiration (ET_0) and the values of crop
120 coefficients (K_c) for citrus provided in Table 12 in FAO-56 (Allen et al. 1998) for
121 determining the amount of irrigation as: $irrigation = K_c * ET_0$. This can under or overestimate
122 the irrigation water needs (Er-Raki et al. 2009). The drip irrigation system used in both sites is
123 installed such that about 40% of the soil field is wetted corresponding to the irrigated part,
124 while 60% of the soil field remains as dry fraction which corresponds to the non-irrigated
125 part. These areas are differentiated by their soil salinity degrees. In Agafay the soil has an
126 electrical conductivity greater than 4 dS m^{-1} which qualifies as a highly saline soil based on
127 Mathieu and Pieltain, (2003). By contrast, at the Saada orchard, the soil is considered non-
128 saline (2 dS m^{-1}) (Sefiani et al., 2017).

129 The climate of these areas is typically Mediterranean. It is characterised by low and irregular
130 rainfall with an annual average of about 240 mm (Khabba et al., 2013). For the period 1972-
131 2012, the average temperature is high in summer ($37 \text{ }^\circ\text{C}$) and low in winter ($5 \text{ }^\circ\text{C}$) (Kharrou et
132 al., 2013). The rainy season is commonly from November to May with a maximum rainfall in
133 November and February. The dry season is about five months, from May to September.

134 **2.2. Experimental Data**

135 Meteorological parameters (rainfall, temperature, humidity, wind speed and direction and
136 solar radiation) were measured by an automatic weather station installed at 2 m above over-
137 irrigated clipped grass. Half-hourly measurements of these parameters are obtained by
138 monitoring wind speed and direction using an anemometer A100R (R. M. Young Company,
139 USA), air temperature and humidity using HMP45AC (Vaisala Oyj, Helsinki, Finland),
140 incoming solar radiation using radiometer (Kipp & Zonen CNR1, Netherlands) and rainfall
141 using a rain gauge. Daily average values of meteorological data were calculated from the half
142 hourly values in order to compute the daily ET_0 (mm day^{-1}), according to the FAO-56
143 Penman–Monteith (Allen et al. 1998). The temporal evolution of daily ET_0 (Figure 2) is
144 typical for the semi-arid climate; low values in winter (1-2 mm), high values in summer (6-8
145 mm) and an annual average of about 1600 mm. For Agafay orchard, the study concerns two
146 years contrasting in their rainfall; 2007 and 2010 are considered as dry (148.3 mm) and rainy
147 (342.6 mm) years respectively.

148 For the two sites Agafay and Saada, actual crop evapotranspiration (ET_{c_act}) was measured by
149 an eddy-covariance system. It consists of a 3D sonic anemometer (CSAT3, Campbell

150 Scientific Ltd.) and a fast response hygrometer (Campbell Scientific Inc., USA). Raw data
151 were sampled at a rate of 20 Hz and were recorded using data loggers (CR5000, Campbell
152 Scientific Ltd). The size of both fields was large enough to meet the required fetch conditions
153 for the eddy covariance system. The reliability of eddy covariance measurements in our
154 studied sites was assessed by analysing the energy balance closure. Indeed, the obtained daily
155 errors of this balance closure were generally less than 10% of available energy (Er-Raki et al.,
156 2012), which can be considered acceptable for the eddy covariance measurements over the
157 tree-orchards (Ezzahar et al., 2007; Er-Raki et al., 2009; Er-Raki et al., 2012).

158 In addition, soil moisture content was measured by 12 Time Domain Reflectometry sensors
159 (TDR) (CS616, Campbell Scientific Ltd.). The TDR are installed in two different locations: 6
160 in the non-irrigated part between the rows and 6 in irrigated part under tree canopies, at depths
161 of 5, 10, 20, 30, 40, and 60 cm, in order to measure the soil water content in different
162 conditions. Measurements were taken at 1 Hz, and 30 min averages stored data loggers
163 (CR23X, Campbell Scientific Ltd.). Finally, a fluxmeter for direct measurement of DP was
164 installed in the Agafay site at a depth of 80 cm, beneath the root zone. Note that the fluxmeter
165 was not installed in the Saada site.

166 **2.3. Methodology**

167 In our study, the deep percolation (DP) losses are defined as the water amounts flowing
168 downwards below root zone. They are evaluated for the two studied sites by using the
169 following soil water balance equation:

$$170 \quad DP = P + I - ET_{c_act} - R + CR \pm \Delta W \quad (1)$$

171 where DP, P, I, ET_{c_act} , R and CR are deep percolation, precipitation, irrigation, actual crop
172 evapotranspiration, runoff and capillary rise from water table respectively. These terms are all
173 in mm.

174 Because the studied sites are both flat and the precipitations are not heavy, R is neglected in
175 the water balance equation. Furthermore, as the water table is deep, depth varied from 15 to
176 80 m (Boukhari et al., 2015), CR was considered to be zero.

177 ΔW is the variation of soil water content in the root zone, defined as:

$$178 \quad \Delta W = W(t) - W(t - 1) \quad (2)$$

179 where $W(t)$ is the water storage at time t in the root zone derived from the layer-wise soil
180 moisture values (θ_i), measured by TDR. The value of ΔW (eq. 2) is positive when water is

181 added to the root zone; otherwise it is null or negative. At a given moment, water storage W
 182 (t) was computed from the values of θ_i ($i = 1, \dots, 6$) and the thickness of each layer (δZ , in
 183 mm) as:

$$184 \quad W(t) = \sum_1^6 (\delta Z_i * \theta_i) \quad (3)$$

185 The relative deep percolation (DP_R) as a percentage of the rate of irrigation or total water
 186 supply (irrigation and rainfall) is expressed respectively as follows:

$$187 \quad DP_{R(I)} = \frac{DP}{I} * 100 \quad (4)$$

$$188 \quad DP_{R(I+P)} = \frac{DP}{I+P} * 100 \quad (5)$$

189 The calculated DP losses and the actual allocated amounts of drip irrigation are analysed at
 190 different time scales, especially for different growing stages: induction, flowering, fruit set,
 191 fruit drop, fruit growth, slowdown growth, maturation and harvest (El Hari, 1992). Note that
 192 this analysis was repeated for two years, 2007 and 2010, in Agafay and during 2004 in Saada
 193 site where the measurements are available. According to Bouazzama and Bahiri, (2008) and
 194 Domingo et al., (2007), one can note that high amount of irrigation is critical in fruit growth
 195 phase (June -October) to increase juice content and fruit size. The water stress during the fruit
 196 drop (May-June) decreases the number of fruit per tree, and this is why water availability in
 197 the soil in this period is important to reduce fruitlet fall (Bouazzama and Bahiri, 2008). Water
 198 stress can also influence fruit quality such as acidity in maturation stage, and reduce fruit
 199 numbers in flowering and fruit set phases (Lado et al., 2014; Käthner et al., 2017). Bellvert et
 200 al. (2016) has investigated the evaluation of water stress throughout different growing seasons
 201 for several fruit tree species by using remotely-sensed indicators.

202 Additionally, in order to assess the adequacy of the water supply at different growing stages,
 203 two indicators are used: depleted fraction (DF) and relative evapotranspiration (RET) indices
 204 (Eq. 4). DF represents the part of the water supply (I+P) that is consumed by the standard
 205 evapotranspiration (ETc), whereas RET allows assessing the occurrence of water deficits (Bos
 206 et al., 2005; Kharrou et al., 2013) defined as ratio of actual crop evapotranspiration (ET_{c_act})
 207 and (ETc):

$$208 \quad DF = \frac{ETc}{I+P} \quad \text{and} \quad RET = \frac{ET_{c_act}}{ETc} \quad (6)$$

209 The value of ETc is estimated using the FAO-56 simple approach (Allen et al., 1998) as the
 210 product of crop coefficient (Kc) and ET_0 . The value of Kc for citrus is taken as 0.65 which is

211 the average value of the ratio between measured (ET_{c_act}) by eddy covariance system and ET_0 .
212 The obtained value of Kc is corroborated by the work of Er-Raki et al. (2009) when they
213 calibrated Kc values for citrus in the same region.

214 For orange trees in arid and semi-arid areas, the critical value of DF is equal to 0.6 (Kharrou
215 et al., 2013). Values of DF between 0.6 and 1.1 are assumed to have no significant effect on
216 growth and yield.

217 The RET index allows the occurrence of water deficits to be assessed (Roerink et al., 1997;
218 Bos et al., 2005), with an acceptable range from 0.75 to 1 (Roerink et al., 1997). The critical
219 value of RET, which is taken to be 0.75, corresponds to the economic threshold suggesting it
220 is reached when water stress has caused a 25% decrease in crop ET. This threshold can be
221 considered acceptable for irrigated agriculture if it does not lead to meaningful quality and
222 quantity losses for farmers, whereas RET values that are lower than 0.75 are considered to
223 involve a water stress that affects the agricultural development of the crop.

224 In this study, the combined analysis of RET and DF indicators is used to identify how
225 irrigation water management allows better crop development through the reduction of water
226 stress (Kharrou et al., 2013).

227 Thus, the diagram (RET, DF) allows the identification of four zones (Kharrou et al., 2013):

- 228 Zone A: “farmer satisfaction”, there is no water stress but irrigation is excessive,
- 229 Zone B: “water manager’s task”, there is no water stress and the irrigation is adequate.
- 230 Zone C: “risk”, there are water stress and excessive irrigation.
- 231 Zone D: “survival”, water stress is induced by a wrong irrigation scheduling.

232 In order to minimise DP, the FAO-56 approach is used to predict water requirement on a daily
233 basis, by calculating the right amount of irrigation (I) without recording any water stress (Ks)
234 and no losses by DP:

$$235 \quad I(i) = DP(i) - P(i) + ET_c(i) + Dr(i - 1) \quad \text{with} \quad DP=0 \quad (7)$$

$$236 \quad Dr(i) = Dr(i - 1) - P(i) - I(i) + ET_c(i) + Dp(i) \quad (8)$$

$$237 \quad Dr(i - 1) = 1000 * (\theta_{fc} - \theta_{i-1}) * Z_r \quad (9)$$

238 where i is the number of the day, θ_{fc} is the soil moisture content at field capacity ($m^3 m^{-3}$), θ_{i-1}
239 is the average soil moisture content in effective root zone ($m^3 m^{-3}$), and Z_r is the rooting depth
240 (m). Dr is the root zone depletion (mm), which measures the difference between the total
241 available water (TAW) and the actual available water. At field capacity, Dr is equal to zero

242 and no water stress occurs (Eq. 10). When soil water is extracted by evapotranspiration, Dr
 243 increases until it exceeds the readily available water (RAW), and water stress will be induced
 244 (Eq. 11).

245 Water stress coefficient (Ks) is expressed as (Allen et al., 1998):

$$246 \quad Dr(i) \leq RAW \quad K_s = 1 \quad (10)$$

$$247 \quad Dr(i) > RAW \quad K_s = \frac{TAW - Dr(i)}{TAW - RAW} \quad (11)$$

$$248 \quad TAW = 1000 * (\theta_{fc} - \theta_{wp}) * Z_r \quad (12)$$

$$249 \quad RAW = p * TAW \quad (13)$$

250 RAW and TAW are the readily available water and the total available water in the root zone
 251 (mm), p is the depletion fraction which is equal to 0.5 for citrus orchards according to FAO-
 252 56 (Table 22, Allen et al., 1998). The TAW depends on the type of soil and the rooting depth
 253 (Kelly et al., 2010; Troy et al., 2013). Recently, Rosa et al., (2016) adjusted both TAW and
 254 RAW under saline conditions, for evapotranspiration partitioning of maize and sweet
 255 sorghum by applying the SIMDualKc approach.

256 In the case of saline soil, such as the Agafay site, the leaching of salinity is essential for crop
 257 growth, development and yield (Visconti et al., 2012). Salt leaching requires adequate
 258 irrigation management, which is based on adding sufficient amounts of water beyond the crop
 259 water requirement for evapotranspiration and photosynthesis (Russo et al., 2009). Salt is
 260 continually added to soils when the irrigation water salinity is higher than tolerable water
 261 salinity value (Naidu et al., 1996; Yoseph and Jim, 2004) which varies for citrus from 0.75 to
 262 2.25 dS m⁻¹ (Richards, 1954).

263 Salts in the soil can reduce evapotranspiration by making soil water less "available" for plant
 264 root extraction (Allen et al., 1998). Salinity stress occurs when the salt concentration,
 265 evaluated by the electrical conductivity of the saturated-soil-paste extract (ECe), is higher
 266 than a given concentration threshold ECe_{threshold} equal to 1.7 dS m⁻¹. In this case we estimate
 267 salinity effect on evapotranspiration reduction by varying the soil electric conductivity from
 268 non-saline condition (1.7 dS m⁻¹) to the high salinity (10 dS m⁻¹), using the following
 269 formulae (Allen et al., 1998):

270 When salinity stress occurs without water stress: Dr < RAW

$$271 \quad K_{s_{salinity}} = 1 - \frac{b}{(K_y * 100)} * (ECe - ECe_{threshold}) \quad (14)$$

272 When soil water stress occurs in addition to salinity stress: $D_r > RAW$, the total stress ($K_{S_{tot}}$)
 273 can be given by:

$$274 \quad K_{S_{tot}} = \left(1 - \frac{b}{(K_y * 100)} * (EC_e - EC_{e_{threshold}}) \right) * \left(\frac{TAW - D_r}{TAW - RAW} \right) = K_{S_{salinity}} * K_S \quad (15)$$

275 where b is the percent yield reduction per unit increase in EC_e ($dS\ m^{-1}$), and K_y is the crop
 276 yield response factor being equal to 1.2 (Table 24, Allen et al., 1998).

277 Citrus yields decrease by about 16% for each $1.0\ dS\ m^{-1}$ over the $EC_{e_{threshold}}$ (Visconti et al.,
 278 2012; FAO, 2003). The crop yield response factor was estimated according to Allen et al.,
 279 (1998) as:

$$280 \quad 1 - \frac{Y_r}{Y_m} = K_y * \left(1 - \frac{ET_{c_{act}}}{ET_c} \right) \quad (16)$$

$$281 \quad \frac{Y_r}{Y_m} = 1 - (EC_e - EC_{e_{threshold}}) * \frac{b}{100} \quad (17)$$

282 where Y_r and Y_m are the real and maximum yields ($kg\ ha^{-1}$), respectively.

283 The amount of water applied to wash out excess salts from the root zone is known as the
 284 leaching fraction (LF) (Plaut et al., 2013; FAO, 2003) and is commonly expressed using the
 285 following relationship (Ayers and Westcot, 1985):

$$286 \quad LF = \frac{EC_{iw}}{5 EC_{threshold} - EC_{iw}} \quad (18)$$

287 where EC_{iw} is electrical conductivity of irrigation water ($dS\ m^{-1}$).

288 **3. Results and Discussion**

289 **3.1. Evaluation of deep percolation (DP)**

290 **3.1.1. DP estimations**

291 The value of DP is estimated by using water balance equation and fluxmeter. For the three
 292 years of this study, the annual $ET_{c_{act}}$ of citrus varied between 786.3 and 818 mm (Table 1).
 293 These values are similar to those reported for citrus orchards in the Haouz region (El Hari et
 294 al., 2010; Er-Raki et al., 2009, 2012). The difference between the annual $ET_{c_{act}}$ and rainfall
 295 was $490\ mm\ year^{-1}$ in Saada, $606\ mm\ year^{-1}$ (2007) and $476\ mm\ year^{-1}$ (2010) in Agafay
 296 (Table 1), with an average value of $524\ mm\ year^{-1}$. This large gap makes irrigation very
 297 critical for citrus growth and yield. However, using the water balance equation shows that the
 298 generated DP is very high, varying from 420.3, 454.8 to 708.6 $mm\ year^{-1}$ with an average of

299 about 501 mm year⁻¹. These correspond to a DP_{R(I+P)} of 38.3, 49.3 and 46.3%, with an average
300 value of 43%.

301 For more analysis of DP, we split the whole season into dry and wet periods. During the dry
302 period, from June to October, about 59.8% (2004) of irrigation was supplied in Saada, and
303 62.8% (2007) and 67.3% (2010) in Agafay. This generates respectively DP rates of about
304 270.5, 240 and 417.5 mm dry-period⁻¹ as well as DP_{R(D)} of 24.5%, 34.7% and 48.1% (Table 2).
305 During the wet period (November-May), the DP is relatively lower, recording an average of
306 about 284 mm, varying from 279.8, 216.7 to 355.5 mm wet-period⁻¹, respectively, which
307 represents DP_{R(D)} values of about 46.1, 41.9 and 53.4% (Table 2). According to those results,
308 the annual DP values are about 500 mm, corresponding to a DP_{R(I+P)} of 43% and equivalent to
309 almost double the habitual annual rainfall in the study region (250 mm).

310 Several studies have estimated DP using water balance method in arid and semi-arid climates
311 by recording annual values of DP_{R(I+P)} of about 11% (García and Castel, 2007). Compared to
312 this value, our two citrus orchards presented high DP values. This result does not affect the
313 validity of the drip irrigation technique, which is known by its high efficiency ranged between
314 80 and 90% (Boman, 2002; Kelly et al., 2010). The observed losses are rather due to the
315 combined effects of an inadequate use of this technique and over-irrigation.

316 Furthermore, direct measurement of DP was performed in 2010 by a fluxmeter installed just
317 under the root zone in the Agafay orchard. Figure 3 shows the cumulative deep percolation
318 measured by the fluxmeter (DP_f) and the one calculated by water balance (DP). The evolution
319 of the cumulative values of DP_f is systematically lower than that of DP. However, the annual
320 values of DP and DP_f are similar; 708.6 and 638.9 mm for DP and DP_f respectively. This
321 difference could be explained by two reasons:

- 322 - The scale used by both methods, since the water balance method calculates DP at
323 parcel scale, while the fluxmeter measures DP at local scale;
- 324 - The rainfall interception and runoff, which are not taken into account by the water
325 balance equation (Eq.1). As reported by García and Castel, (2007), rainfall
326 interception by trees is an important component of the water balance as it could
327 present 8% of rainfall.

328 After a preliminary evaluation of deep percolation by using direct measurement (fluxmeter)
329 and soil water balance, the question left to address is to determine the most important factors
330 such as soil water content, physiological and management responsible on the DP losses.

331 **3.1.2. Soil water content and DP losses**

332 The evaluation of DP losses is assessed by studying the variation of soil moisture content (θ_i)
333 in the root zone. For bare soil between the rows in the un-irrigated part of the field, Figure 4
334 presents an example of the temporal evolution of the soil moisture in 60-80 cm depth (lower
335 limit of root zone). In this part, which covers about 60% of the bare soil, the average soil
336 moisture in the root zone varies between the wilting point ($\theta_{wp}= 0.12 \text{ mm}^3 \text{ mm}^{-3}$) and the field
337 capacity ($\theta_{fc}= 0.26 \text{ mm}^3 \text{ mm}^{-3}$). DP takes place only on rainy days when the soil moisture
338 exceeds θ_{fc} .

339 For the irrigated part of the field along tree rows in Agafay and Saada sites, the soil moisture
340 in 60-80 cm depth is frequently above θ_{fc} (Figure 5). Therefore, DP losses were occurring
341 almost throughout both dry and wet periods due to the high frequency of irrigation events.

342 **3.1.3. DP as a function of growth stages**

343 Knowing that some part of water supply can be used by the plant and other part can be lost by
344 direct soil evaporation and/or by DP, it is crucial to estimate the amount of water lost by DP
345 which is the main objective of this present study. The supplied water is split into crop water
346 use (ET_{c_act}) and DP in each crop stage. Figure 6 illustrates an example of irrigation amount
347 according to the phenological phases. The results show that the higher irrigation values are
348 recorded during fruit growth stage, occurring in summer. In this stage, irrigation were 552
349 mm and 582.4 mm in 2007 and 2010 in Agafay and 239.7 mm in 2004 in Saada site,
350 representing about 54.4%, 50.52% and 33.4% of annual irrigation. In descending order, the
351 irrigation rate of the other phases at Agafay (2007, 2010) and Saada (2004) are: 16.2%,
352 17.2%, 19.7% for fruit drop phase; 9.6%, 10.7%, and 10.4% for maturation, 9.6%, 9.9%,
353 9.7% for flowering and fruit set; 2.4%, 2.7%, 3.3% for induction; and 2%, 1.5%, 2.9% for
354 harvest.

355 The higher values of DP losses which equal 200 mm, with $DP_{R(i)}$ of about 35%, are recorded
356 during fruit growth stage (Figure 6). Though this is an important growth period and water
357 demand is high ($ET_{c_act} \approx 390 \text{ mm}$), the irrigation in this stage is largely overdosed (about 560
358 mm). During the other phases, the DP quantities (mm) are relatively lower, but still important
359 by comparison to the irrigation amounts (Figure 7). This explains that a major part of supplied
360 water is lost by DP when the phenological activities and evapotranspiration are low.

361 **3.1.4. Evaluation of water supply adequacy**

362 The evaluation of water supply adequacy by using the diagram RET-DF shows that all
363 phenological phases are in zone A and B of Figure 8, which is consistent with the above
364 findings (Figure 7):

- 365 - Zone A includes the phases characterised by excess irrigation, recording a DF value
366 less than 0.6. For Agafay, these phases are fruit growth, slowdown growth, maturation
367 and harvest for 2007 and 2010 seasons. In Saada case, the phases were flowering,
368 maturation and harvest. This results shows that the orange trees were largely over-
369 irrigated. Consequently, these phases need removed to zone B.
- 370 - Zone B includes the phases characterised by an adequate use of irrigation water,
371 recording DF values between 0.6 and 1.1. These phases are induction, flowering, fruit
372 set, and fruit drop for Agafay, and induction, fruit drop, fruit growth, slowdown
373 growth and fruit set, for Saada.

374 According to these results, the Saada site is characterised by more adequate use of irrigation
375 during the majority of its growth stages than the Agafay site. This is expected since the
376 Agafay site has a high level of soil salinity that needs more water for salt leaching and then
377 more DP losses. This aspect is discussed further in the following section.

378 **3.2. Impact of rainfall and soil salinity on DP**

379 **3.2.1. Effects of rainfall on DP losses**

380 To analyse the effective role of rainfall in citrus water supply and its impact on DP losses, we
381 compare the data of Agafay recorded in the dry year 2007 (148 mm) and the rainy year 2010
382 (343 mm). Despite the high rainfall in 2010, the supplied irrigation (1188 mm) was higher
383 than 2007 (1061 mm). Consequently the DP losses are greater (708.6 mm) in 2010 than in
384 2007 (454.8 mm) (Table 1). Even in the wet year of 2010 the drip irrigation alone exceeds the
385 ET_{c_act} by 31% (Figure 9).

386 At a weekly scale, the farmers supplied irrigations in five weeks in 2007 and nine in 2010
387 (examples giving in Table 3), although the rainfall amounts were adequate to fulfil crop water
388 need (ET_{c_act}). Such behaviour attests to the inappropriate application of irrigation: the wrong
389 quantity is delivered at the wrong moment. Consequently, the DP reached high values, with
390 an average of $34.6 \text{ mm week}^{-1}$ (Figure 9). The way irrigation is applied by the farmer was not
391 appropriate for controlling DP losses.

392 **3.2.2. Impacts on DP of measures to control soil salinity**

393 In Agafay site, the high soil salinity (about 4 dS m^{-1}) could explain the applied over-irrigation.
394 In this case, the irrigation water is used in excess for leaching soil salts in order to avoid root
395 dieback and leaf loss of citrus (Sheng et al., 2002; Ayars et al., 2012). For Agafay orange, the
396 irrigation water exceeds ET_{c_act} by about 306.8 and 370.5 mm in dry and wet years,

397 respectively. These DP amounts correspond to about 29 and 31% of irrigation water,
398 respectively. However, Robert and Richard (1999) reported that only 17% irrigation excess is
399 needed for salt leaching. Also Barnard et al., (2010) and Plaut et al. (2013) found that in sandy
400 loam soil, similar to the Agafay site, 20% of irrigation excess is sufficient to leach salts from
401 the root zone. This result shows that, in Agafay orchard, the applied water quantities are still
402 higher than is needed to address the salinity issue.

403 **3.3. Irrigation water management to control DP losses and crop water stress**

404 The optimisation of irrigation water scheduling, in time and quantity, was performed by using
405 FAO-56 simple approach for the two orange sites in order to avoid both water stress and deep
406 percolation (i.e. $K_s=1$ and $DP=0$ at all times). Based on the equation (7), the obtained results
407 show that annual values of recommended irrigations without taking into account the salinity
408 issue are 685 and 530 mm for Agafay (2007 and 2010) and 558 mm for Saada. By adding the
409 amount of rainfall (149, 343 and 296 mm, respectively), the total supplied coincides with the
410 adequate citrus water requirement ($845 \text{ mm year}^{-1} = K_c * ET_0 = 0.65 * 1300 \text{ mm year}^{-1}$)
411 (FAO, 2003; Er-Raki et al., 2009; El Hari et al., 2010). The recommended irrigation can then
412 save approximately 39 and 45% of the irrigation in Saada and Agafay, respectively.

413 As the Agafay site is under high soil salinity, it is of interest to quantify the effect of this
414 parameter on the stress and on the amount of irrigation needed. The total stress ($K_{s_{tot}}$)
415 increases (Figure 10) when soil electrical conductivity exceeds the tolerable salinity threshold
416 of citrus (1.7 dS m^{-1}). In this case, the impact of salinity is remedied by adding an additional
417 irrigation to the recommended amount. This supplemental irrigation is used for salinity
418 leaching and not used by the crop, and then lost by DP. The question addressed is how much
419 amount of water should be used as a leaching fraction (LF).

420 Based on equation (18), when the soil electrical conductivity is 2.5 dS m^{-1} , the leaching
421 fraction is 17% of water supply. This fraction equals an additional irrigation of about 116 and
422 90 mm year^{-1} for 2007 and 2010, respectively. By considering these amounts, the annual
423 recommended irrigation needed to avoid water and salinity stress ranges between 766 mm
424 (2007) and 624 mm (2010).

425 Taking into account the water and salinity stress and DP losses, the recommended irrigations
426 in Saada and Agafay allowed us to plot all the growing phases in zone B with $DF=1$. This is
427 likely to ensure an effective irrigation strategy for optimising citrus irrigation schedules, while
428 avoiding water stress and DP losses. The recommended irrigation can then save
429 approximately 39 and 37% of the irrigation in Saada and Agafay, respectively. Saving

430 irrigation water in such proportions is equivalent to save 3520 m³ ha⁻¹ year⁻¹ in Saada and
431 2950 m³ ha⁻¹ year⁻¹ (2007) to 5640 m³ ha⁻¹ year⁻¹(2010) in Agafay. The average quantity of
432 irrigation water that could be saved is about 4295 m³ ha⁻¹ year⁻¹. If we consider 6000 ha of
433 citrus in the Haouz plain cultivated and irrigated in the same conditions of Agafay site, the
434 overall saved amount of water would be 25.8 10⁶ m³ year⁻¹.

435 **4. Conclusion**

436 The paper investigates deep percolation (DP) in citrus orchards with drip irrigation under
437 semi-arid climate and develops a method based on the FAO-56 model to define irrigation
438 schemes and to optimise irrigation in non- saline and saline soil conditions.

439 The results obtained show that, under the irrigation conditions of the study, the DP calculated
440 by the water balance equation is very high; varying from 420 to 709 mm year⁻¹ with a relative
441 DP_{R(D)} value of about 38.3 and 49.2% for non-saline and saline soils, respectively. Direct
442 measurements of DP confirmed these estimations by recording a DP_f of about 638.9 mm year⁻¹
443 ¹. This is in accordance with high values of root zone moisture, which almost exceed the soil
444 moisture at field capacity. The evolution of DP across the phenological phases has given
445 additional information on the higher value of DP losses of about 200 mm with DP_{R(D)} of 35%
446 recorded during the fruit growth stage.

447 The FAO-56 simple approach was used to assess the appropriate irrigation amount in case of
448 saline and non-saline soils. The results shows that, by taking into account the rainfall, this
449 model recommends an amount of irrigation much lower than that actually applied by the
450 farmers. Following the model simulations, it seems possible to save about 39% of water
451 supply at the Saada site, with non-saline soil, and about 30% to 47% at the Agafay site, with
452 saline soil. This study has demonstrated that a reasonable drip irrigation scheduling is
453 necessary for water saving.

454 As a main perspective of the study, the evaluation of DP losses would be important
455 information to estimate groundwater recharge beneath the irrigated fields. However, regarding
456 the heterogeneous lithology of the Haouz plain and its deep groundwater, the DP contribution
457 to the aquifer recharge remains an important scientific issue.

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645

Figure captions

646 Figure 1: Location of the study sites Agafay and Saada.

647 Figure 2: Daily reference evapotranspiration (dotted line: ET_0) calculated following the FAO–
648 Penman–Monteith equation and precipitation events (vertical bars : P) in the study orchards: Agafay
649 during 2007 (a) , 2010 (b) and Saada during 2004 (c).

650 Figure 3: Cumulative deep percolation measured by fluxmeter (solid line: DP_f) and deep percolation
651 calculated by water balance (dashed line: DP) in Agafay for 2010.

652 Figure 4: Daily rainfall (vertical bars: P), deep percolation (dashed line: DP) and soil moisture
653 (continuous line: θ_i) for bare soil in **depth** 60-80 cm (example of Agafay site, 2007). The upper and the
654 lower horizontal continuous lines corresponds to the soil moisture at field capacity (θ_{fc}) and at wilting
655 point (θ_{wp}), respectively. The areas of soil moisture variation **above** θ_{fc} , between θ_{fc} and θ_{wp} and
656 below θ_{wp} correspond to the deep percolation, available soil water and unavailable soil water zones,
657 respectively.

658 Figure 5: Daily water supply (vertical bars: I+P), deep percolation (dashed line: DP) and soil moisture
659 (continuous line: θ_i) for irrigated part in depth 60-80 cm (example of Agafay site, 2010). The upper and
660 the lower horizontal continuous lines corresponds to the soil moisture at field capacity (θ_{fc}) and at
661 wilting point (θ_{wp}), respectively. The areas of soil moisture variation above θ_{fc} , between θ_{fc} and θ_{wp}
662 and below θ_{wp} correspond to the deep percolation, available soil water and unavailable soil water
663 zones, respectively.

664 Figure 6: Variation of deep percolation (dashed line: DP), actual crop evapotranspiration (—◆—:
665 ETc_{act}) and irrigation (vertical bars: I) according to the phenological stages during 2007 in Agafay.

666 Figure 7: Relative **deep** percolation evolution according to the phenological stages during (grey
667 vertical bars : 2007) and (white vertical bars: 2010) in Agafay and (black vertical bars: 2004) in
668 Saada.

669 Figure 8: Combined analysis of relative evapotranspiration (RET) and depleted fraction (DF) for all
670 phenological phases: (◆: induction), (■: flowering), (▲: Fruit set), (△: Fruit drop), (○: Fruit
671 growth), (●: slowdown growth), (□: maturation) and (◇: harvest) for Agafay (2007: (a)), (2010: (b))
672 and Saada in (2004: (c)).

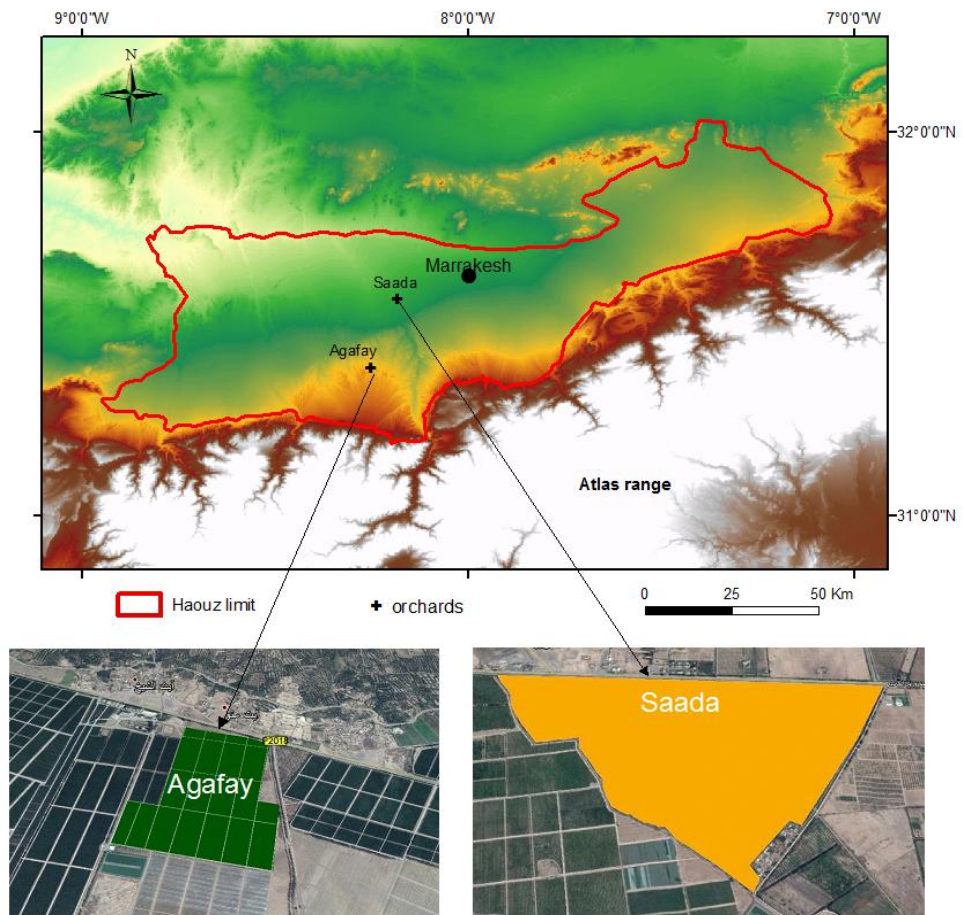
673 Figure 9: Weekly evolution of precipitation (black vertical bars: P), irrigation (grey vertical bars: I),
674 actual crop evapotranspiration (◆: ETc_{act}) and deep percolation (dashed line: DP) during (2007:
675 (a) and (2010: (b)) in Agafay.

676 Figure 10: Effect of the variation of soil electric conductivity (E_{ce}) on the total stress coefficient
677 (dashed line: $K_{s_{tot}}$). The required irrigation for each value of E_{ce} is also shown (◆). The horizontal
678 continuous line corresponds to the amount of recommended irrigation without salinity issue.

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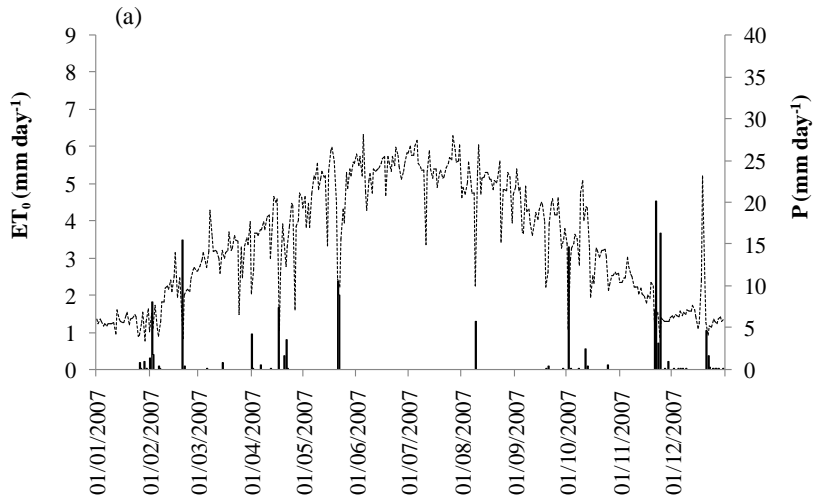
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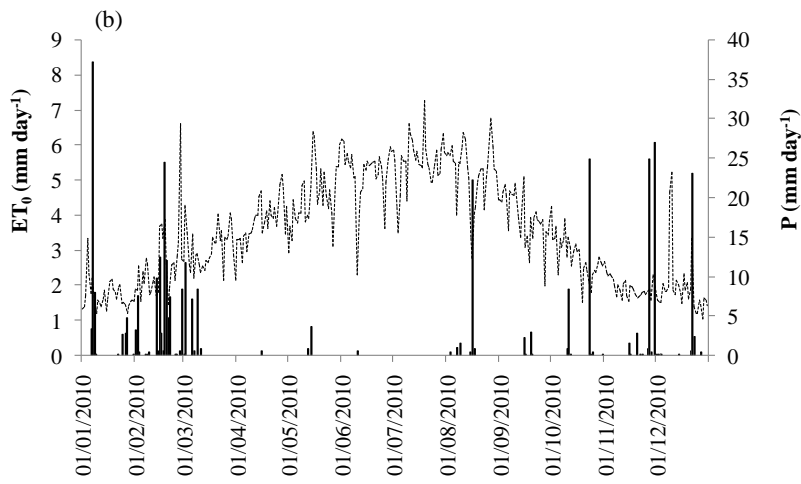


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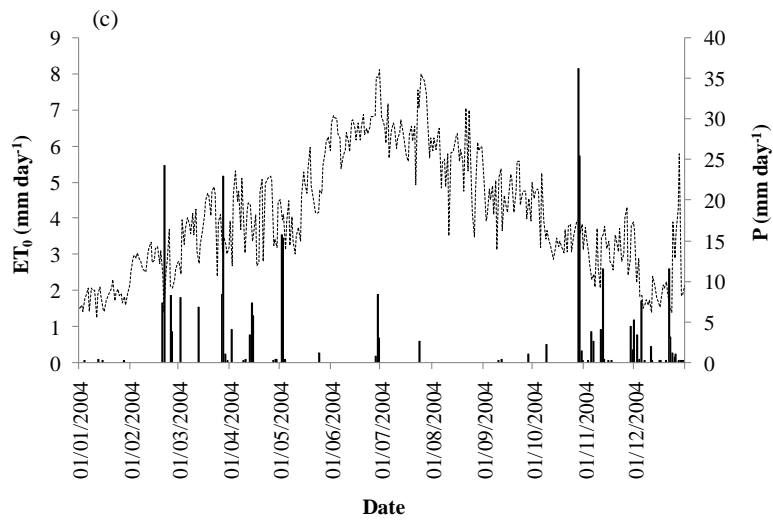
Figure 1



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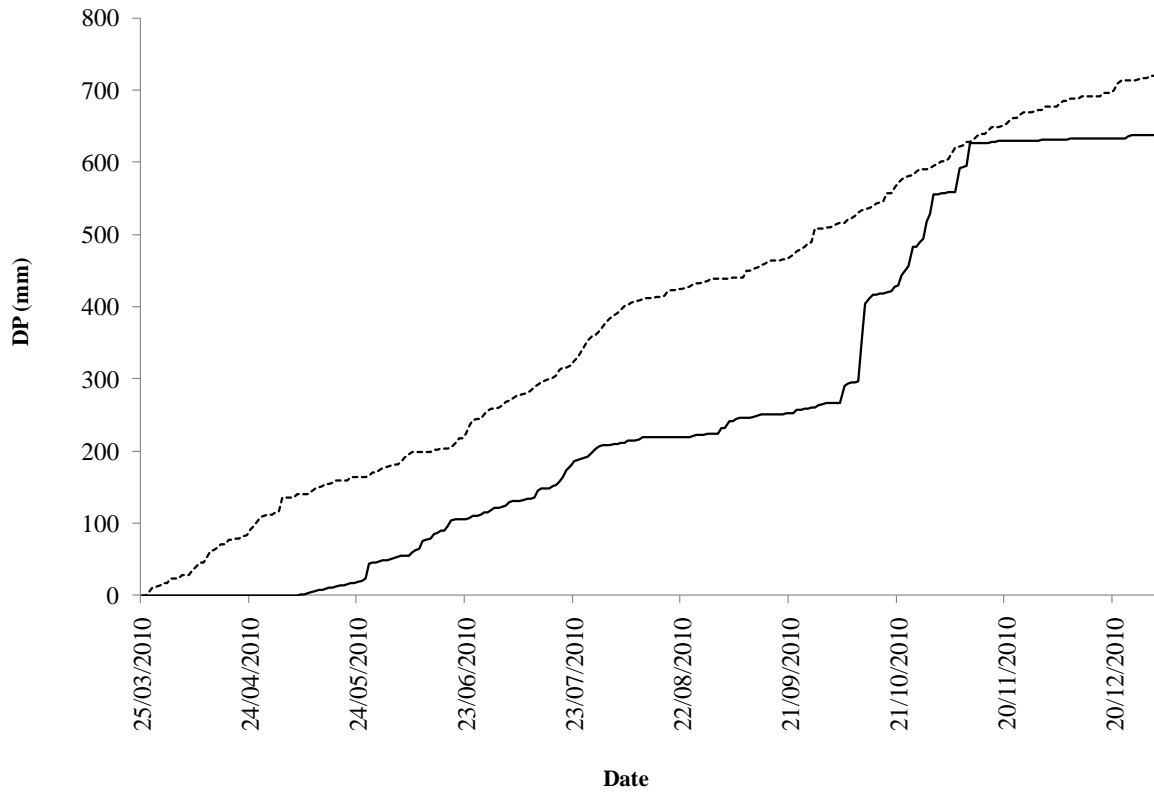
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Figure 2

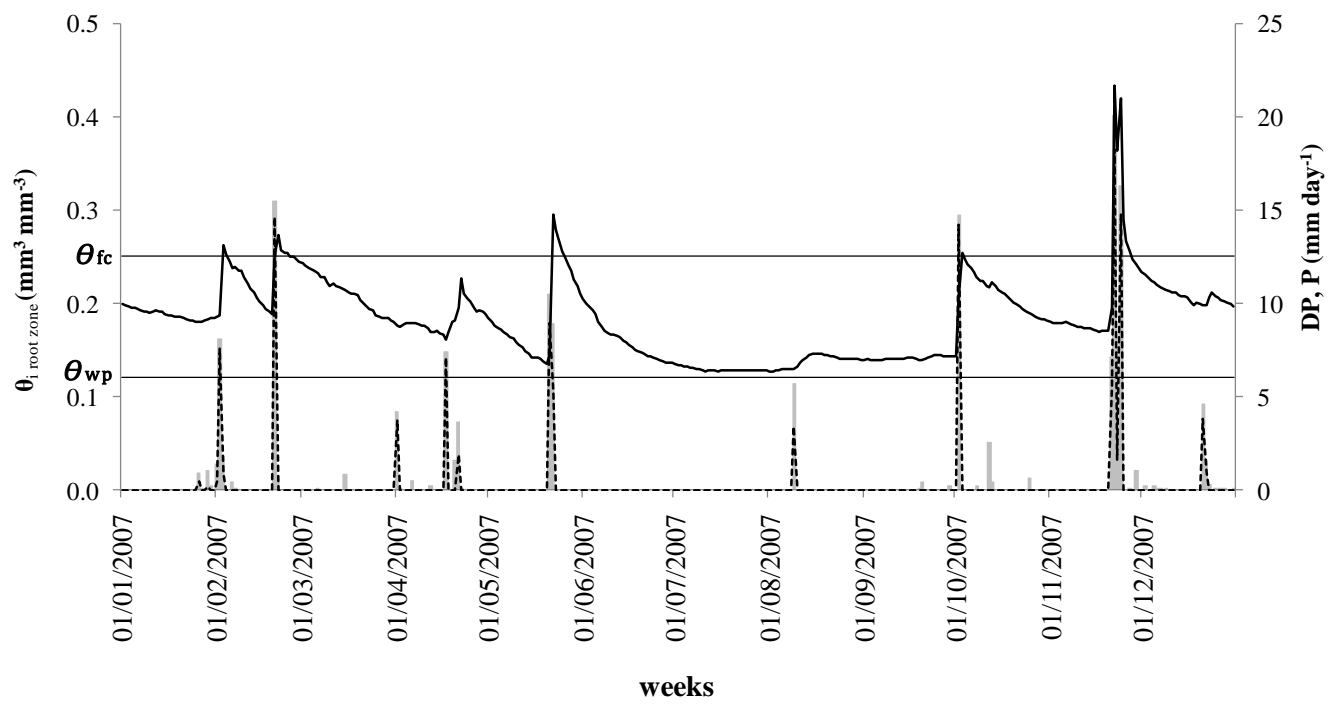
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Figure 3

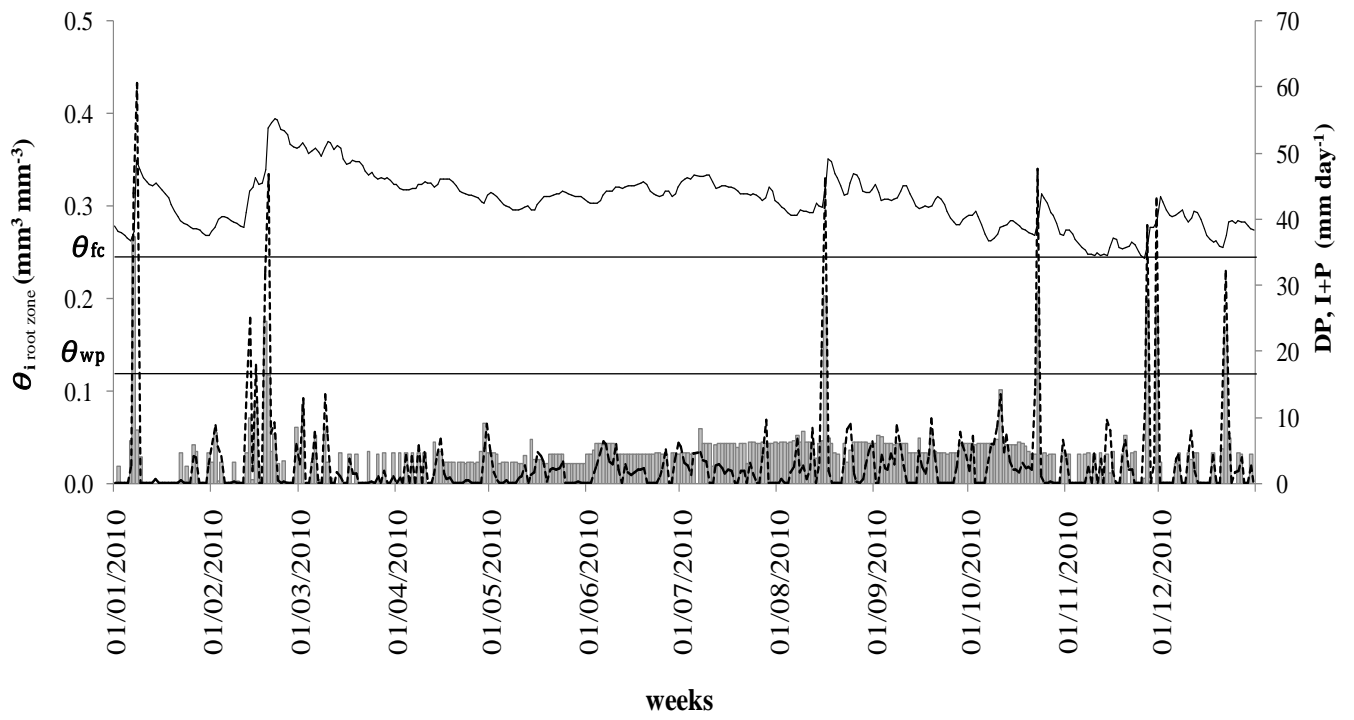
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Figure 4

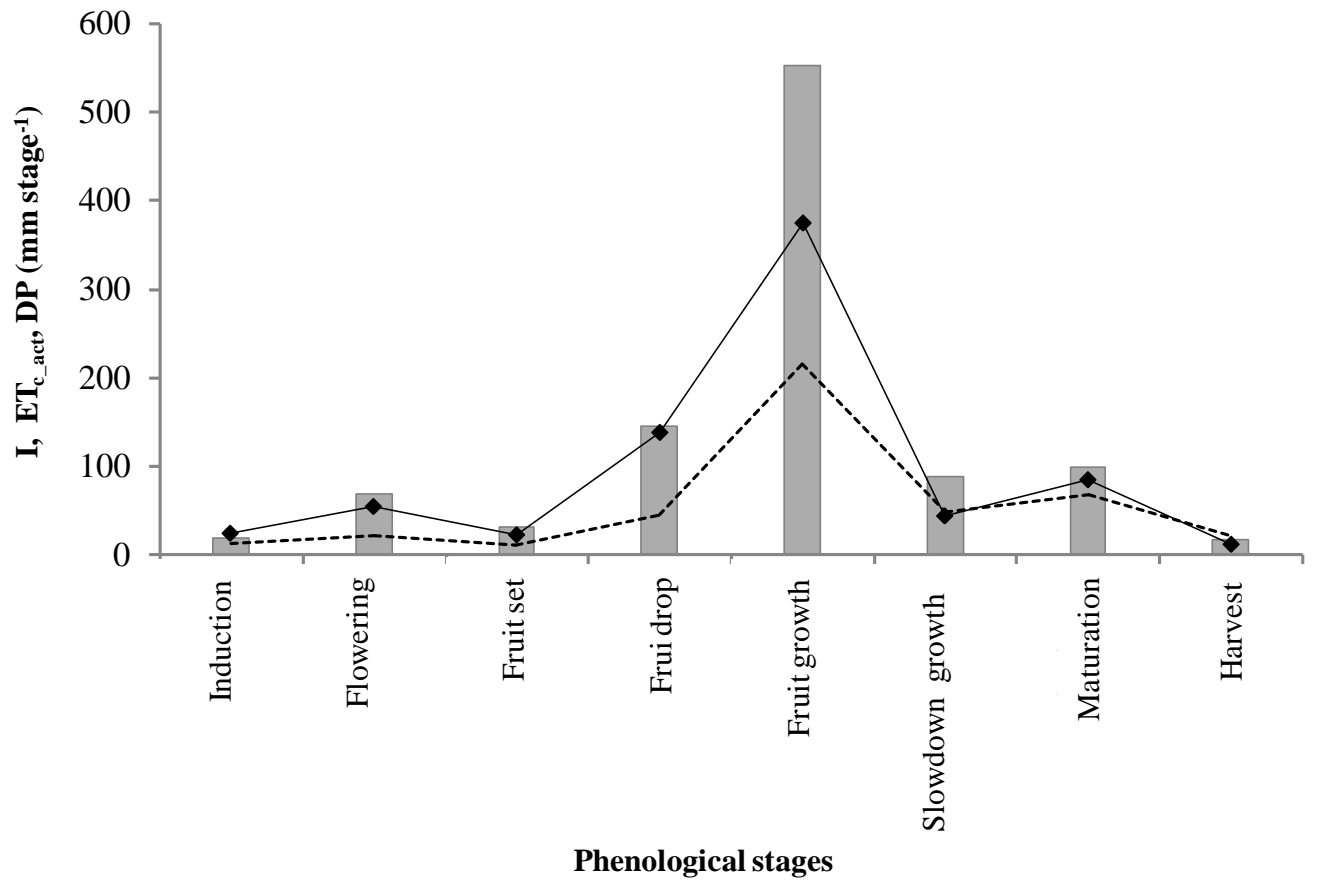
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Figure 5

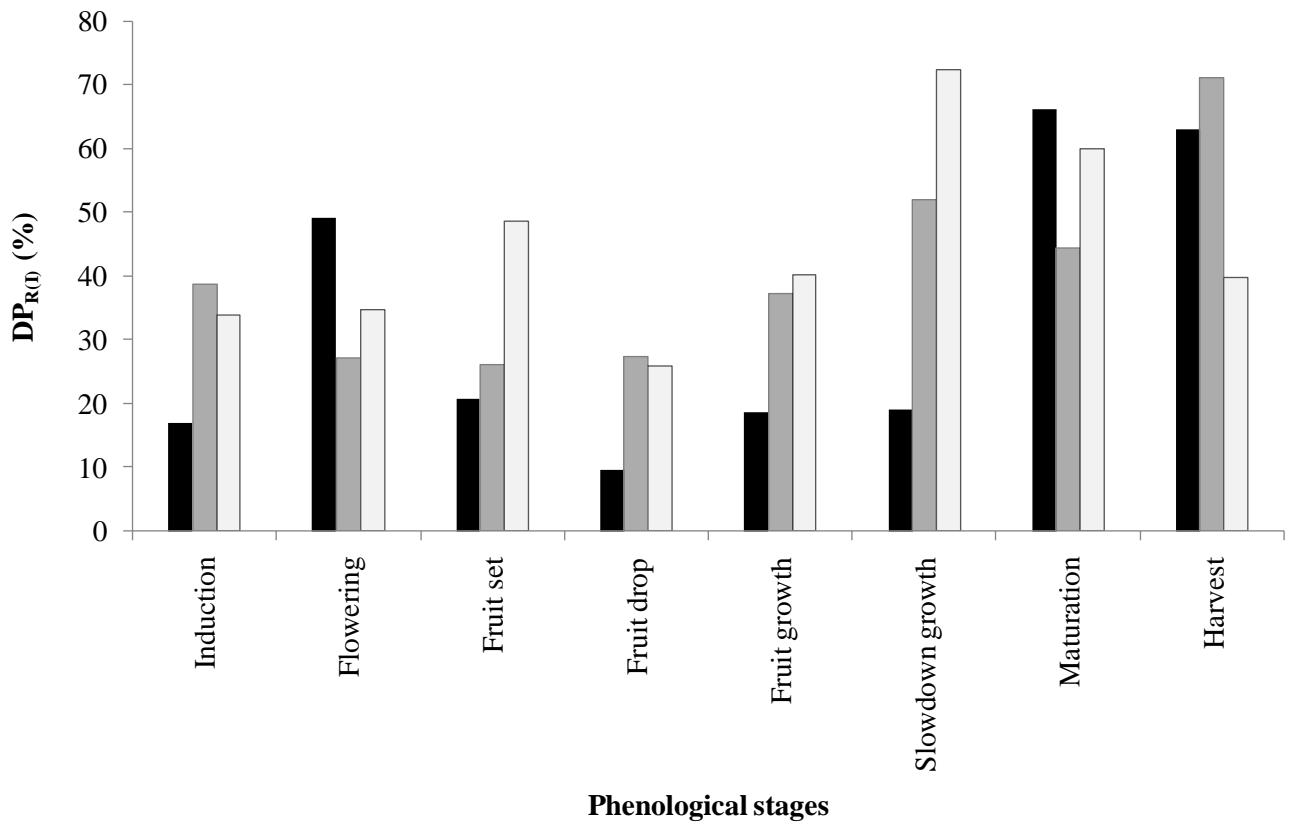
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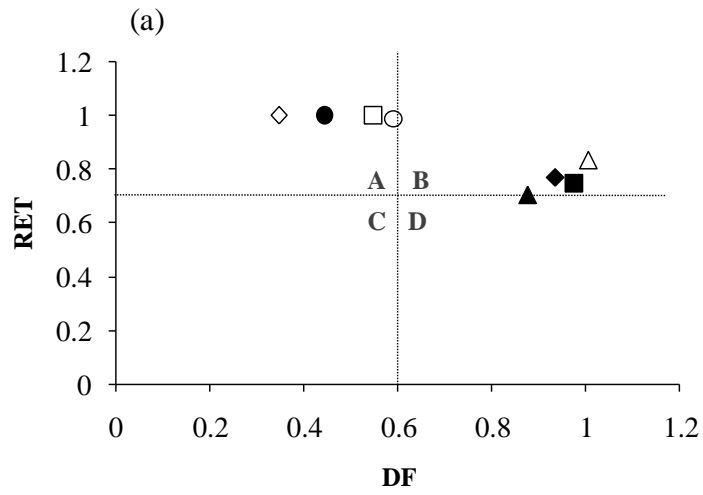
Figure 6

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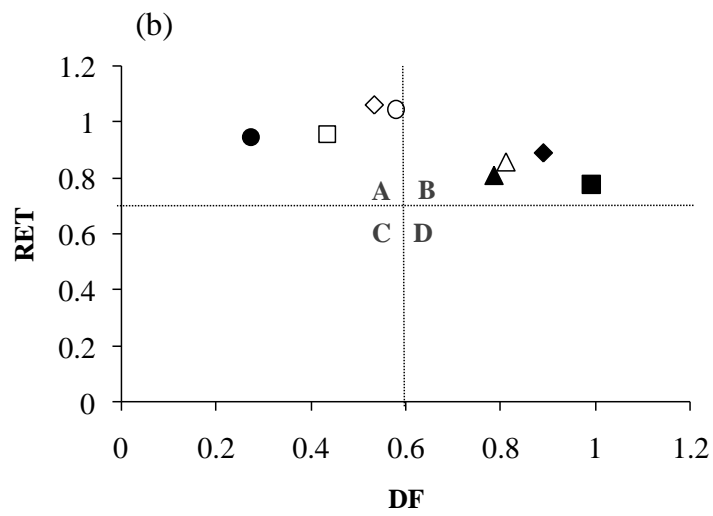


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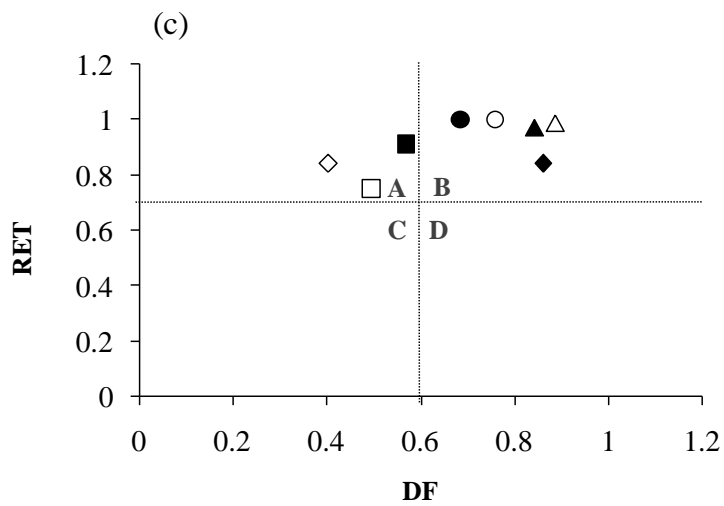
Figure 7



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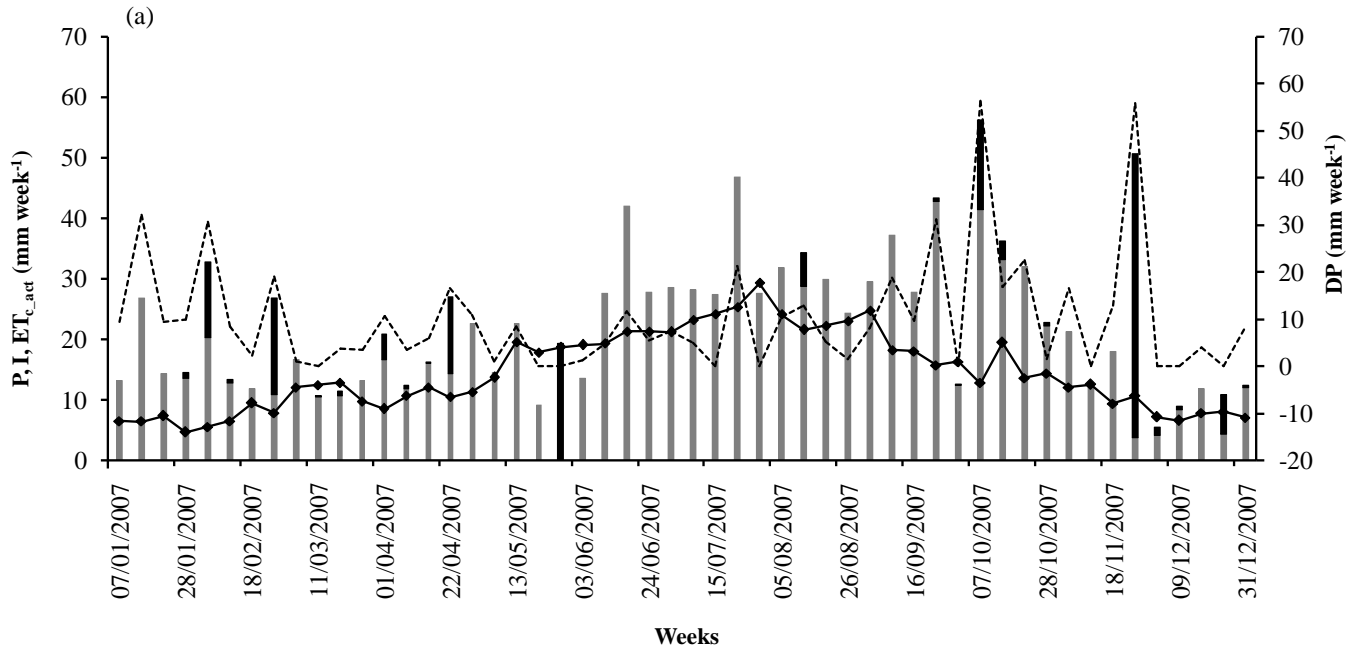
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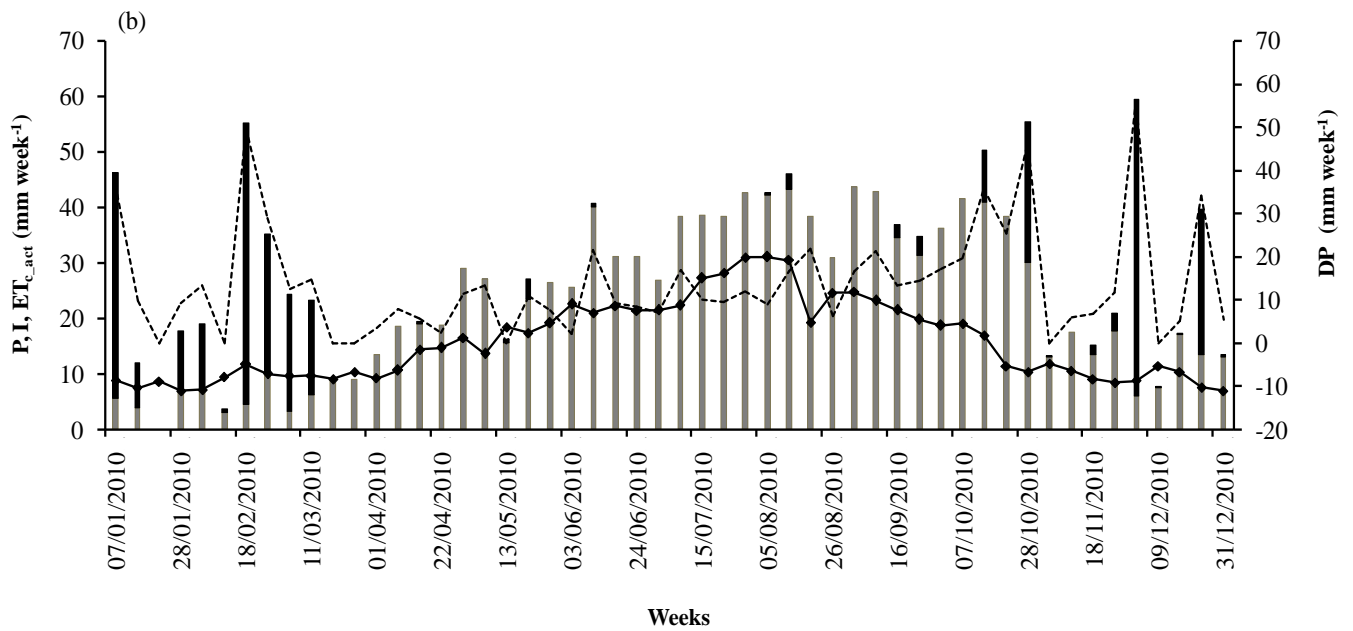
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Figure 8

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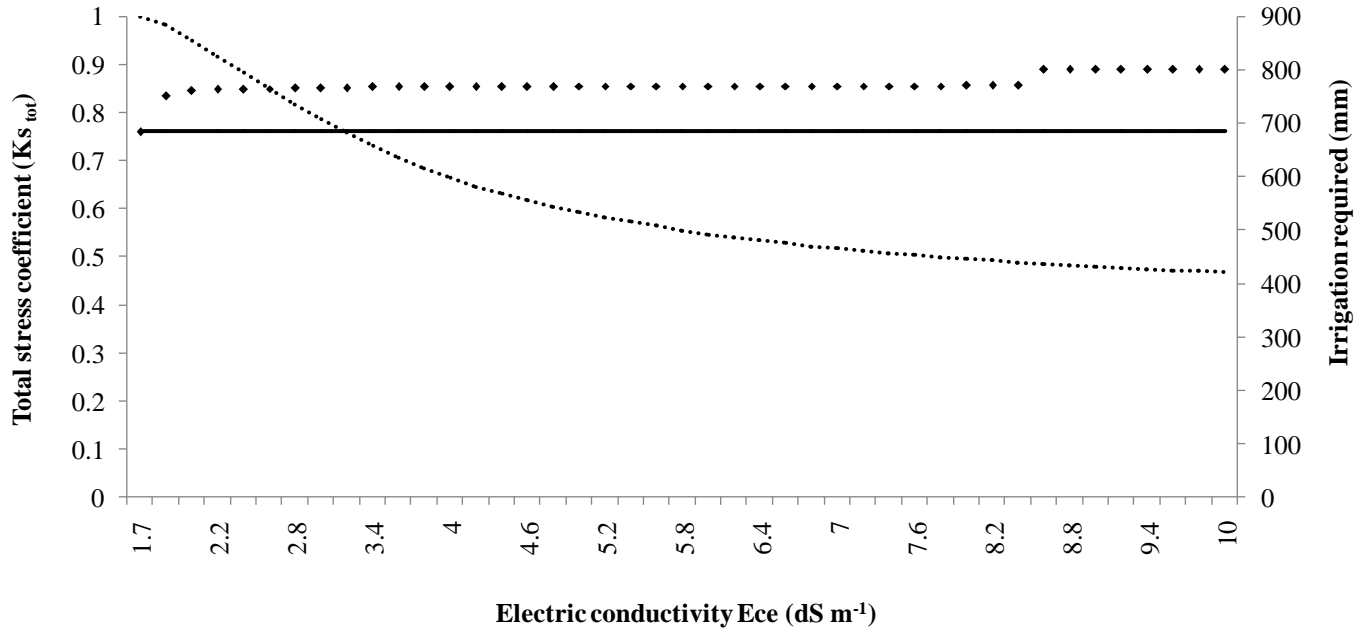
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Figure 9

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Figure 10

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808 **Table 1: Annual values of actual crop evapotranspiration ($ET_{c,act}$), rainfall (P), Irrigation (I), deep**
 809 **percolation (DP) and relative deep percolation (DP_R) in non-saline (Saada) and saline soil (Agafay) sites.**

orchards	years	$ET_{c,act}$ (mm)	P (mm)	I (mm)	DP (mm)	$DP_{R(I+P)}$ (%)*
Saada	2004	786.3	295.8	910.4	420.3	38.3
Agafay	2007	754.8	148.3	1061.3	454.8	49.3
	2010	818.1	342.6	1188.6	708.6	46.3
	Average	786.4	245.4	1124.9	581.7	47.8
Overall average		786.4	270.6	1017.7	501	43

810 * $DP_{R(P+I)}$ (%) is calculated in daily basis

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812 **Table 2: Seasonal values of irrigation (I), deep percolation (DP) and relative deep percolation (DP_R) in**
 813 **non-saline (Saada) and saline soil (Agafay) orchards.**

orchards		saada			Agafay					
Years		2004			2007			2010		
Variables		I (mm)	DP(mm)	$DP_{R(I)}$ (%)	I (mm)	DP(mm)	$DP_{R(I)}$ (%)	I (mm)	DP(mm)	$DP_{R(I)}$ (%)
season	wet	365.7	279.8	46.1	394.5	216.7	41.9	388.2	355.5	53.4
	dry	544.7	270.5	24.6	667.1	240	34.7	800.4	417.5	48.1

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816 **Table 3: Weekly rates of irrigation (I), actual crop evapotranspiration ($ET_{c,act}$), deep percolation (DP) and**
 817 **relative deep percolation (DP_R) in presence of precipitations in saline soil (Agafay).**

weeks	P (mm)	I (mm)	$ET_{c,act}$ (mm)	DP (mm)	$DP_{R(I+P)}$ (%)
17-23/12/2010	25	13.6	7.6	34.6	89
21-27/12/2007	6.8	8.6	6.7	12.8	83

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