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► To cite this version:

Houda Nassah, Salah Er-Raki, Saïd Khabba, Younes Fakir, Fatima Raibi, et al.. Evaluation and analysis of deep percolation losses of drip irrigated citrus crops under non-saline and saline conditions in a semi-arid area. *Biosystems Engineering*, 2018, 165, pp.10-24. 10.1016/j.biosystemseng.2017.10.017 . hal-01940007v2

HAL Id: hal-01940007

<https://hal.science/hal-01940007v2>

Submitted on 24 Dec 2018

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

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

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

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

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

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

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

14*Corresponding author address:

15Dr. Salah Er-Raki

16 LP2M2E, Département de physique, Faculté des Sciences et Techniques (FSTG), Cadi Ayyad
17University. 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

20Abstract

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

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

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

391. Introduction

40In the southern Mediterranean region, as in many arid and semi-arid regions of the world,
41water 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
43estimated that about 83% of available resources is dedicated to agriculture with an efficiency
44lower than 50% (Chehbouni et al., 2008). In Morocco, this waste of water has several origins
45including 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
47irrigation is mostly determined according to the water availability so that the actual plant
48water needs are generally not taken into account. In addition, the traditional flooding systems
49are 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

51program for irrigation conversion from flood to drip (PMV, 2013). However, the obtained
52results for DP are surprising as an inadequate use of the drip technique may lead to substantial
53water losses (Khabba et al., 2013). It has been shown that the DP losses for the drip irrigation
54sites are in the range 29-41 % of water input while they are relatively lower for flood
55irrigation, ranging from 26 to 31 % (Khabba et al., 2013). Moreover, as the soil salinity may
56limits plant growth (Ayars et al., 2012), the farmers usually apply excessive irrigation to leach
57soil salinity out of root layer or root zone and hence avoid salinity stress (Visconti et al.,
582012). In general, over-irrigation amounts are arbitrary and largely estimated. In our study
59basin, this situation leads to an overexploitation of groundwater, with a level decreasing from
601 to 3 m year⁻¹ (Le Page et al., 2012; Boukhari et al., 2015).

61In order to preserve water resources, the rationalisation of irrigation water use is necessary.
62An accurate estimation of the water consumed by evapotranspiration (ET) and lost by DP
63would provide a basis for improving irrigation efficiency (Kharrou et al., 2013; Belaqziz et
64al., 2014; Xianwen et al., 2016).

65Regarding ET, crop coefficients and associated measurements have been reported in the
66literature and used to test, develop and calibrate a range of ET models (Allen et al., 2011; Er-
67Raki et al., 2013). DP is commonly assessed by the soil water balance equation when both ET
68and water supply irrigation and rainfall are available (Sammis et al., 1983). The method has
69been used under different irrigation techniques and for various crops (Vázquez et al., 2006;
70Wang et al., 2012). DP can also be measured by direct methods such as lysimeters (Allen et
71al., 1991; Kim et al., 2011; Duncan et al., 2016), or fluxmeters (Deurer et al., 2008; Gee et al,
722009). However, these methods are expensive (Upreti et al., 2015) and may disrupt flow,
73causing errors in the measured drainage (Gee et al., 2009).

74Other indirect methods have also been used such as the hydraulic method (Qinbo et al., 2011;
75Allman et al., 2015), temperature measurements in the unsaturated zone (Constantz et al.,
762003; Landon et al., 2016), and geochemical tracers (Stonestrom et al., 2003; Stephens et al.,
772006).

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

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

912. MATERIALS AND METHODS

922.1. Sites description

93The study was conducted on two citrus orchards: Agafay and Saada (Figure 1). The Agafay
94site covers an area of 38 ha approximately 44 km southwest of Marrakech city (31°29'
9550.19"N, 008°25' 02"W). The field experiment was carried out from 2006 to 2013 in a
96mandarin orchard planted in July 2000. The trees were planted at a spacing of 4 m in rows and
976 m between rows, which is about 35% ground cover. The height of trees was about 3 m and
98the depth of the root zone around 0.6 m. This depth was determined by making five pits near
99to the tree's root zone. The crop was maintained in over-irrigated conditions by drip irrigation:
100the irrigation frequency was almost every day without taking into account rainfall events.
101Moreover, the amount of water applied by the farmers during each irrigation event varied
102between 2 and 9 mm day⁻¹ depending on climatic conditions. The Agafay site is divided into
103three sectors and irrigated within 24 hours at a rate varying from 28 to 60 m³ ha⁻¹. Note that
104irrigation 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
10650% sand). According to the pedo-transfer function of Wosten et al. (1997) the soil moisture
107at field capacity (θ_{fc}) and wilting point (θ_{wp}) are 0.26 and 0.12 mm³ mm⁻³, which corresponds
108to 156 and 72 mm at the root zone at the experimental plot, respectively.
109The Saada site is located approximately 15 km west of Marrakech city (31°37'36''N,
11008°09'35''W). It covers an area of 128 ha and is planted with 13-year old mandarin trees; the
111field experiment was conducted during 2004. The orange trees were placed at a spacing of 5
112m in rows and 3 m between rows, with 70% of the ground cover fraction. The average height
113of the trees was about 3.15 m and the depth of the root zone was about 0.6 m. The Saada
114citrus was maintained in over-irrigated conditions by daily irrigation varied from 2 to 5 mm,
115depending on climatic conditions. The orchard is divided into several sectors, but all irrigated
116on the same day with a rate varying from 4 to 56 m³ ha⁻¹. The soils have high sand and low

117clay contents (12% clay, 38% silt, and 50% sand). More details about the two sites can be
118found in the studies by Er-Raki et al. (2009) and Er-Raki et al. (2012).
119For both sites, the farmers use the reference evapotranspiration (ET_0) and the values of crop
120coefficients (K_c) for citrus provided in Table 12 in FAO-56 (Allen et al. 1998) for
121determining the amount of irrigation as: $irrigation = K_c * ET_0$. This can under or overestimate
122the irrigation water needs (Er-Raki et al. 2009). The drip irrigation system used in both sites is
123installed such that about 40% of the soil field is wetted corresponding to the irrigated part,
124while 60% of the soil field remains as dry fraction which corresponds to the non-irrigated
125part. These areas are differentiated by their soil salinity degrees. In Agafay the soil has an
126electrical conductivity greater than 4 dS m^{-1} which qualifies as a highly saline soil based on
127Mathieu and Pieltain, (2003). By contrast, at the Saada orchard, the soil is considered non-
128saline (2 dS m^{-1}) (Sefiani et al., 2017).
129The climate of these areas is typically Mediterranean. It is characterised by low and irregular
130rainfall with an annual average of about 240 mm (Khabba et al., 2013). For the period 1972-
1312012, the average temperature is high in summer ($37 \text{ }^\circ\text{C}$) and low in winter ($5 \text{ }^\circ\text{C}$) (Kharrou et
132al., 2013). The rainy season is commonly from November to May with a maximum rainfall in
133November and February. The dry season is about five months, from May to September.

1342.2. Experimental Data

135Meteorological parameters (rainfall, temperature, humidity, wind speed and direction and
136solar radiation) were measured by an automatic weather station installed at 2 m above over-
137irrigated clipped grass. Half-hourly measurements of these parameters are obtained by
138monitoring wind speed and direction using an anemometer A100R (R. M. Young Company,
139USA), air temperature and humidity using HMP45AC (Vaisala Oyj, Helsinki, Finland),
140incoming solar radiation using radiometer (Kipp & Zonen CNR1, Netherlands) and rainfall
141using a rain gauge. Daily average values of meteorological data were calculated from the half
142hourly values in order to compute the daily ET_0 (mm day^{-1}), according to the FAO-56
143Penman–Monteith (Allen et al. 1998). The temporal evolution of daily ET_0 (Figure 2) is
144typical for the semi-arid climate; low values in winter (1-2 mm), high values in summer (6-8
145mm) and an annual average of about 1600 mm. For Agafay orchard, the study concerns two
146years contrasting in their rainfall; 2007 and 2010 are considered as dry (148.3 mm) and rainy
147(342.6 mm) years respectively.
148For the two sites Agafay and Saada, actual crop evapotranspiration (ET_{c_act}) was measured by
149an eddy-covariance system. It consists of a 3D sonic anemometer (CSAT3, Campbell

150Scientific Ltd.) and a fast response hygrometer (Campbell Scientific Inc., USA). Raw data
 151were sampled at a rate of 20 Hz and were recorded using data loggers (CR5000, Campbell
 152Scientific Ltd). The size of both fields was large enough to meet the required fetch conditions
 153for the eddy covariance system. The reliability of eddy covariance measurements in our
 154studied sites was assessed by analysing the energy balance closure. Indeed, the obtained daily
 155errors of this balance closure were generally less than 10% of available energy (Er-Raki et al.,
 1562012), which can be considered acceptable for the eddy covariance measurements over the
 157tree-orchards (Ezzahar et al., 2007; Er-Raki et al., 2009; Er-Raki et al., 2012).

158In 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
 160in the non-irrigated part between the rows and 6 in irrigated part under tree canopies, at depths
 161of 5, 10, 20, 30, 40, and 60 cm, in order to measure the soil water content in different
 162conditions. 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
 164installed in the Agafay site at a depth of 80 cm, beneath the root zone. Note that the fluxmeter
 165was not installed in the Saada site.

1662.3. Methodology

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

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

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

174Because the studied sites are both flat and the precipitations are not heavy, R is neglected in
 175the water balance equation. Furthermore, as the water table is deep, depth varied from 15 to
 17680 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:

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

179where W (t) is the water storage at time t in the root zone derived from the layer-wise soil
 180moisture 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:

$$184 \quad W(t) = \sum_{i=1}^6 (\delta Z_i * \theta_i) \quad (3)$$

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:

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

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

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 (ET_c), 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 (ET_c):

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

209 The value of ET_c is estimated using the FAO-56 simple approach (Allen et al., 1998) as the
 210 product of crop coefficient (K_c) and ET_0 . The value of K_c 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 K_c is corroborated by the work of Er-Raki et al. (2009) when they
 213 calibrated K_c 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 with $DP = DP(i) - P(i) + ET_c(i) + Dr(i)$ (7)

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

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

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). D_r is the root zone depletion (mm), which measures the difference between the total
 241available water (TAW) and the actual available water. At field capacity, D_r is equal to zero
 242and no water stress occurs (Eq. 10). When soil water is extracted by evapotranspiration, D_r
 243increases until it exceeds the readily available water (RAW), and water stress will be induced
 244(Eq. 11).

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

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

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

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

$$249 RAW = p * TAW$$

250RAW 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-
 25256 (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
 254RAW under saline conditions, for evapotranspiration partitioning of maize and sweet
 255sorghum by applying the SIMDualKc approach.

256In the case of saline soil, such as the Agafay site, the leaching of salinity is essential for crop
 257growth, development and yield (Visconti et al., 2012). Salt leaching requires adequate
 258irrigation management, which is based on adding sufficient amounts of water beyond the crop
 259water requirement for evapotranspiration and photosynthesis (Russo et al., 2009). Salt is
 260continually added to soils when the irrigation water salinity is higher than tolerable water
 261salinity value (Naidu et al., 1996; Yoseph and Jim, 2004) which varies for citrus from 0.75 to
 2622.25 $dS m^{-1}$ (Richards, 1954).

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

270When salinity stress occurs without water stress: $D_r < RAW$

$$271 \quad (14) \quad K_{s_{\text{salinity}}} = 1 - \frac{b}{(K_y + 100)} * (EC_e - EC_{e_{\text{threshold}}})$$

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

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

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 $EC_{e_{\text{threshold}}}$ (Visconti et al.,
 278 2012; FAO, 2003). The crop yield response factor was estimated according to Allen et al.,
 279 (1998) as:

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

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

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):

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

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

2883. Results and Discussion

2893.1. Evaluation of deep percolation (DP)

2903.1.1. 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 $ET_{c_{\text{act}}}$ 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 $ET_{c_{\text{act}}}$ 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

297critical for citrus growth and yield. However, using the water balance equation shows that the
298generated DP is very high, varying from 420.3, 454.8 to 708.6 mm year⁻¹ with an average of
299about 501 mm year⁻¹. These correspond to a DP_{R(I+P)} of 38.3, 49.3 and 46.3%, with an average
300value of 43%.

301For more analysis of DP, we split the whole season into dry and wet periods. During the dry
302period, from June to October, about 59.8% (2004) of irrigation was supplied in Saada, and
30362.8% (2007) and 67.3% (2010) in Agafay. This generates respectively DP rates of about
304270.5, 240 and 417.5 mm dry-period⁻¹ as well as DP_{R(I)} of 24.5%, 34.7% and 48.1% (Table 2).
305During the wet period (November-May), the DP is relatively lower, recording an average of
306about 284 mm, varying from 279.8, 216.7 to 355.5 mm wet-period⁻¹, respectively, which
307represents DP_{R(I)} values of about 46.1, 41.9 and 53.4% (Table 2). According to those results,
308the annual DP values are about 500 mm, corresponding to a DP_{R(I+P)} of 43% and equivalent to
309almost double the habitual annual rainfall in the study region (250 mm).

310Several studies have estimated DP using water balance method in arid and semi-arid climates
311by recording annual values of DP_{R(I+P)} of about 11% (García and Castel, 2007). Compared to
312this value, our two citrus orchards presented high DP values. This result does not affect the
313validity of the drip irrigation technique, which is known by its high efficiency ranged between
31480 and 90% (Boman, 2002; Kelly et al., 2010). The observed losses are rather due to the
315combined effects of an inadequate use of this technique and over-irrigation.

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

322-The scale used by both methods, since the water balance method calculates DP at
323parcel scale, while the fluxmeter measures DP at local scale;

324-The rainfall interception and runoff, which are not taken into account by the water
325balance equation (Eq.1). As reported by García and Castel, (2007), rainfall
326interception by trees is an important component of the water balance as it could
327present 8% of rainfall.

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

3313.1.2. Soil water content and DP losses

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

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

3423.1.3. DP as a function of growth stages

343Knowing that some part of water supply can be used by the plant and other part can be lost by
344direct soil evaporation and/or by DP, it is crucial to estimate the amount of water lost by DP
345which is the main objective of this present study. The supplied water is split into crop water
346use (ET_{c_act}) and DP in each crop stage. Figure 6 illustrates an example of irrigation amount
347according to the phenological phases. The results show that the higher irrigation values are
348recorded during fruit growth stage, occurring in summer. In this stage, irrigation were 552
349mm and 582.4 mm in 2007 and 2010 in Agafay and 239.7 mm in 2004 in Saada site,
350representing about 54.4%, 50.52% and 33.4% of annual irrigation. In descending order, the
351irrigation rate of the other phases at Agafay (2007, 2010) and Saada (2004) are: 16.2%,
35217.2%, 19.7% for fruit drop phase; 9.6%, 10.7%, and 10.4% for maturation, 9.6%, 9.9%,
3539.7% for flowering and fruit set; 2.4%, 2.7%, 3.3% for induction; and 2%, 1.5%, 2.9% for
354harvest.

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

3613.1.4. Evaluation of water supply adequacy

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

365-Zone A includes the phases characterised by excess irrigation, recording a DF value
366less than 0.6. For Agafay, these phases are fruit growth, slowdown growth, maturation
367and harvest for 2007 and 2010 seasons. In Saada case, the phases were flowering,
368maturation and harvest. This results shows that the orange trees were largely over-
369irrigated. Consequently, these phases need removed to zone B.

370-Zone B includes the phases characterised by an adequate use of irrigation water,
371recording DF values between 0.6 and 1.1. These phases are induction, flowering, fruit
372set, and fruit drop for Agafay, and induction, fruit drop, fruit growth, slowdown
373growth and fruit set, for Saada.

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

3783.2. Impact of rainfall and soil salinity on DP

3793.2.1. Effects of rainfall on DP losses

380To analyse the effective role of rainfall in citrus water supply and its impact on DP losses, we
381compare 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
383than 2007 (1061 mm). Consequently the DP losses are greater (708.6 mm) in 2010 than in
3842007 (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).

386At 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
388need (ET_{c_act}). Such behaviour attests to the inappropriate application of irrigation: the wrong
389quantity is delivered at the wrong moment. Consequently, the DP reached high values, with
390an average of 34.6 mm week⁻¹ (Figure 9). The way irrigation is applied by the farmer was not
391appropriate for controlling DP losses.

3923.2.2. 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.

4033.3. 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 mm year⁻¹ = K_c * ET₀ = 0.65 * 1300 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 $3520 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ in Saada and
431 $2950 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ (2007) to $5640 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ (2010) in Agafay. The average quantity of
432 irrigation water that could be saved is about $4295 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$. 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 $25.8 \times 10^6 \text{ m}^3 \text{ year}^{-1}$.

4354. 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 $DP_{R(I)}$ 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 $638.9 \text{ mm year}^{-1}$.
443 This is in accordance with high values of root zone moisture, which almost exceeded 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 $DP_{R(I)}$ 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.

458Acknowledgments: This research was conducted within the International Joint Laboratory
459TREMA (<http://trema.ucam.ac.ma>) and GEOHYD laboratory (Cadi Ayyad University).
460Funding were provided by SAGESSE (PPR program funded by the Moroccan Ministry of
461Higher Education), ANR AMETHYST project (ANR-12-TMED-0006-01), H2020 REC
462project (645642) financed by the Marie Skłodowska-Curie Research and Innovation Staff
463 Exchange (RISE). The first author was awarded mobility researcher training from the PHC
464Maghreb 32592VE/14MAG22. Thanks also to Moroccan CNRST for awarding a PhD
465scholarship to H. Nassah. We thank the farmers for their collaboration.

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Figure captions

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

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

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

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

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

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

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

Figure 8: Combined analysis of relative evapotranspiration (RET) and depleted fraction (DF) for all phenological phases: (◆: induction), (□: flowering), (□: Fruit set), (□: Fruit drop), (○: \square growth), (□: slowdown growth), (□: maturation) and (□: harvest) for Agafay (2007: (a)), (2010: \square) and Saada in (2004: (c)).

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

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

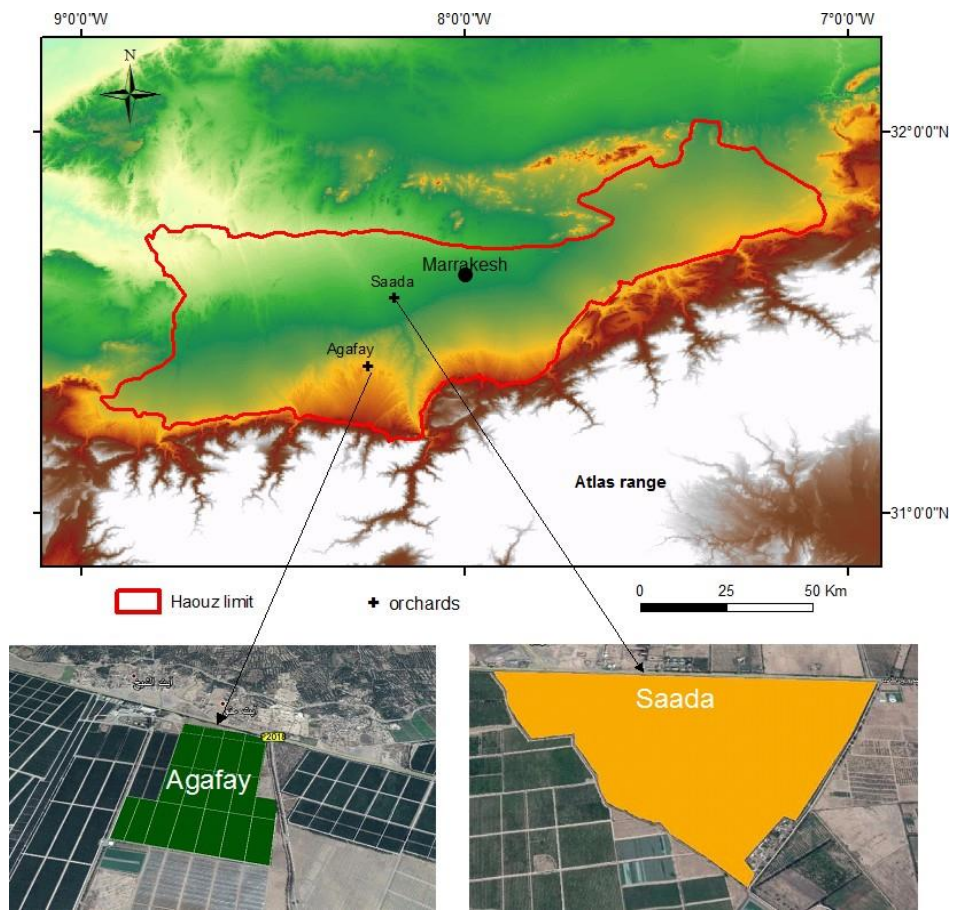


Figure 1

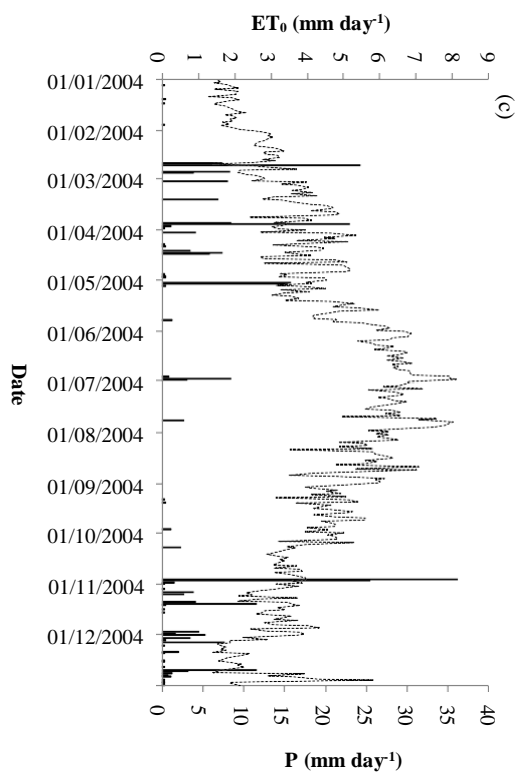
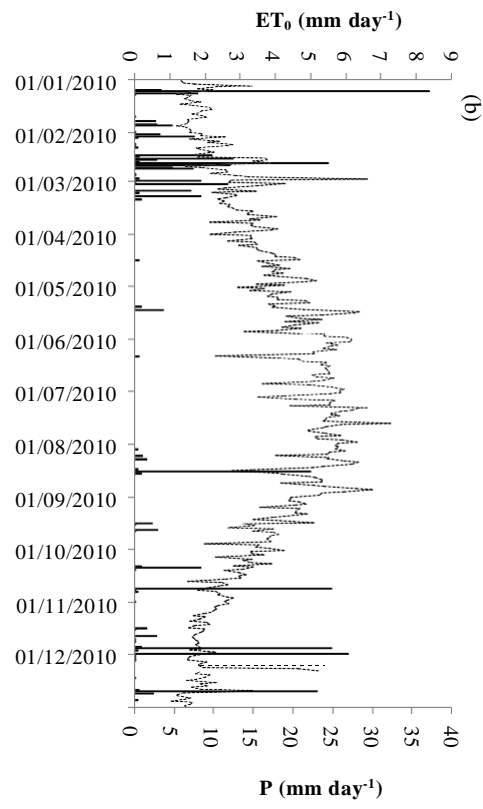
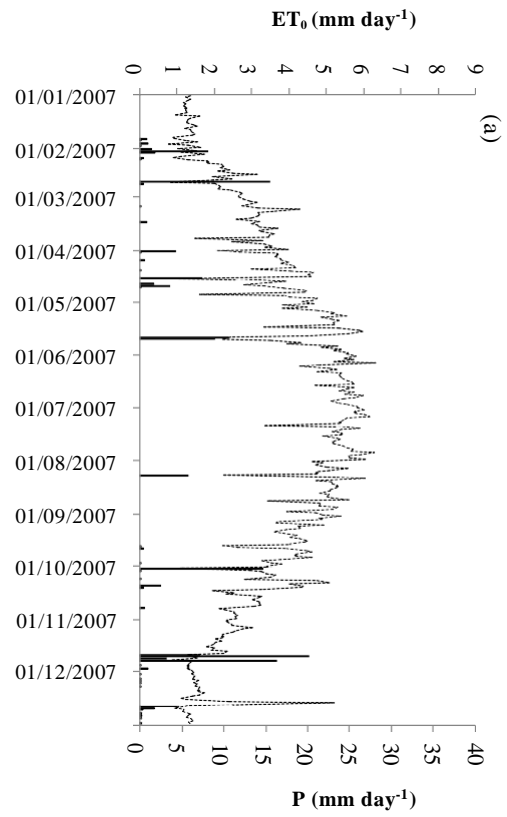


Figure 2

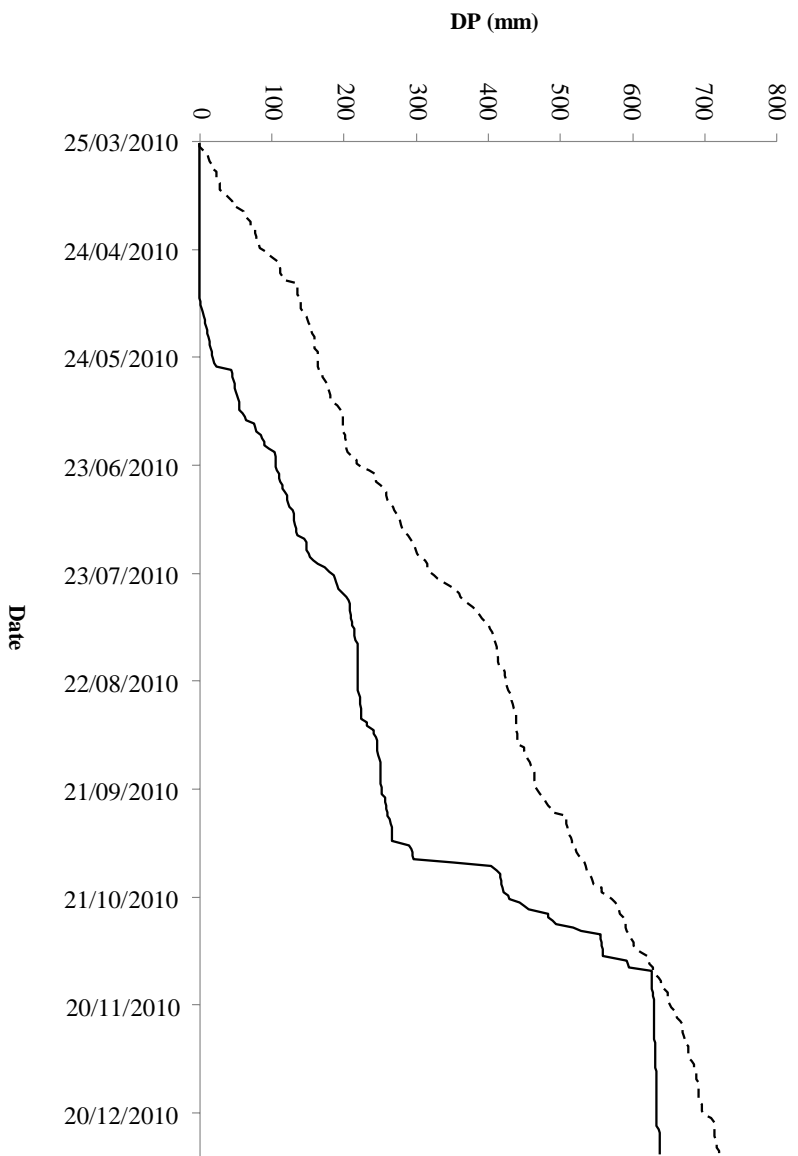


Figure 3

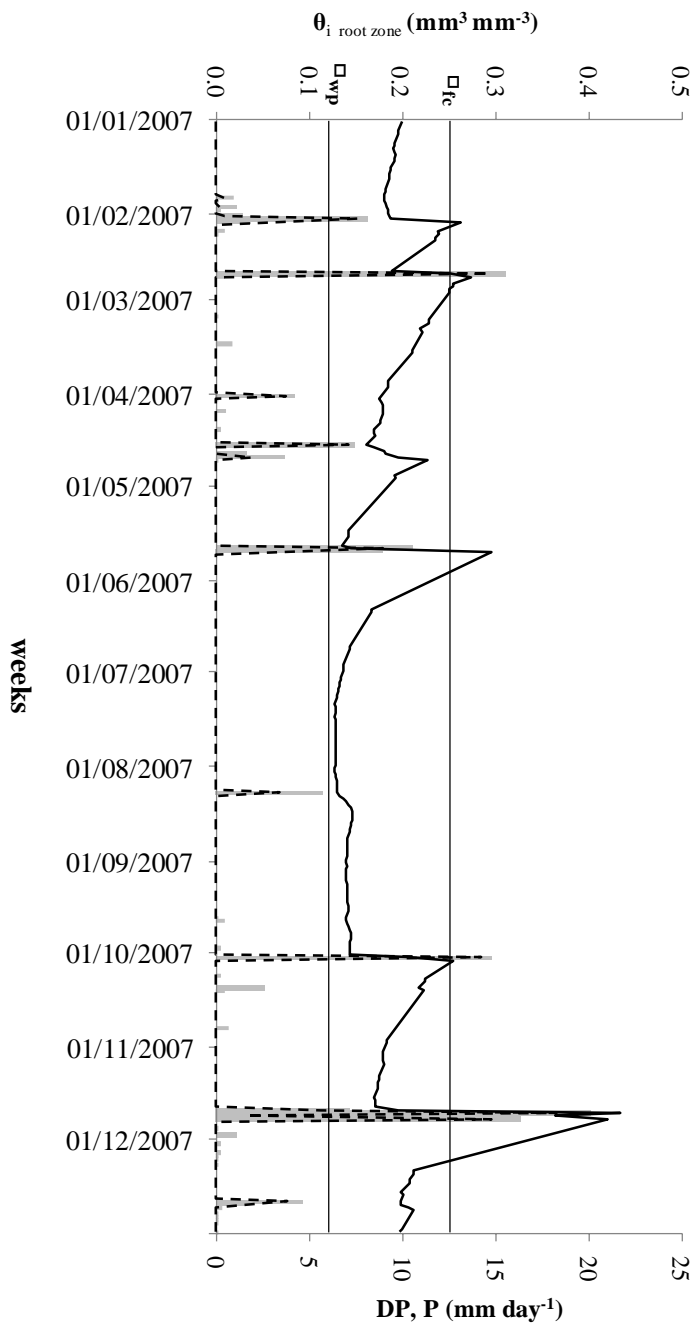


Figure 4

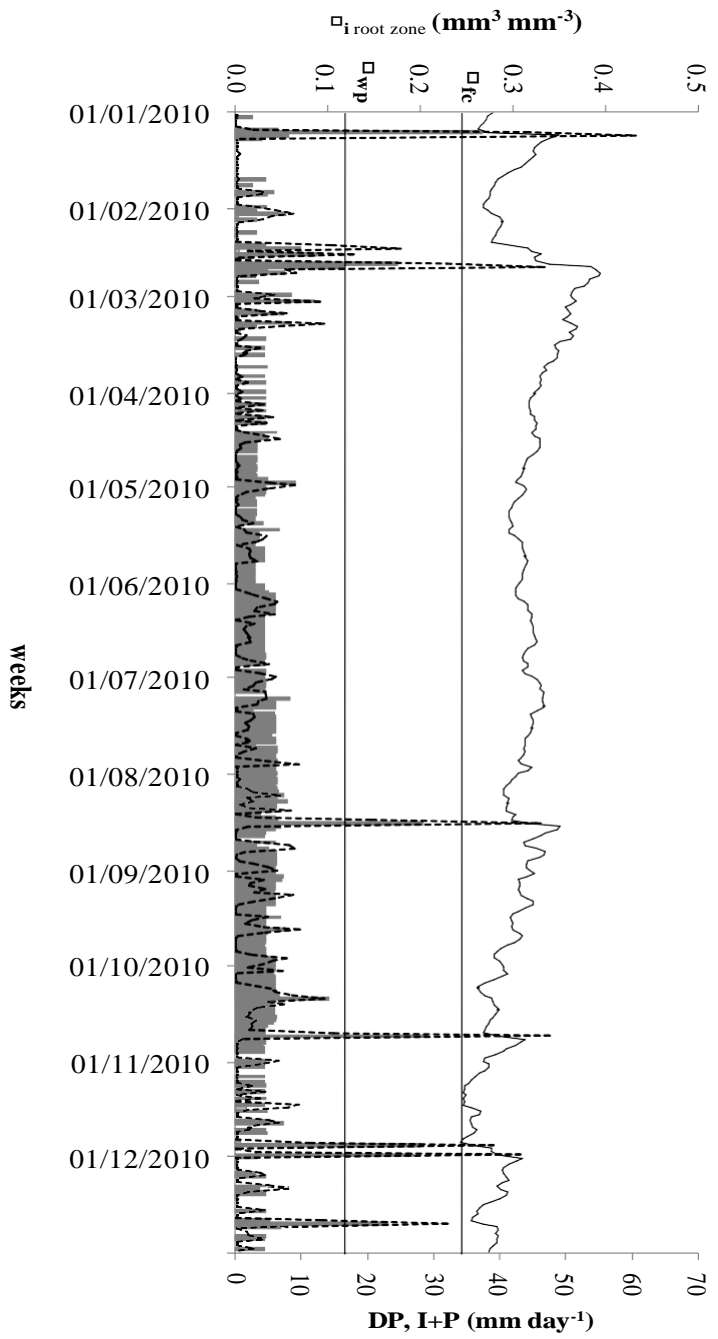


Figure 5

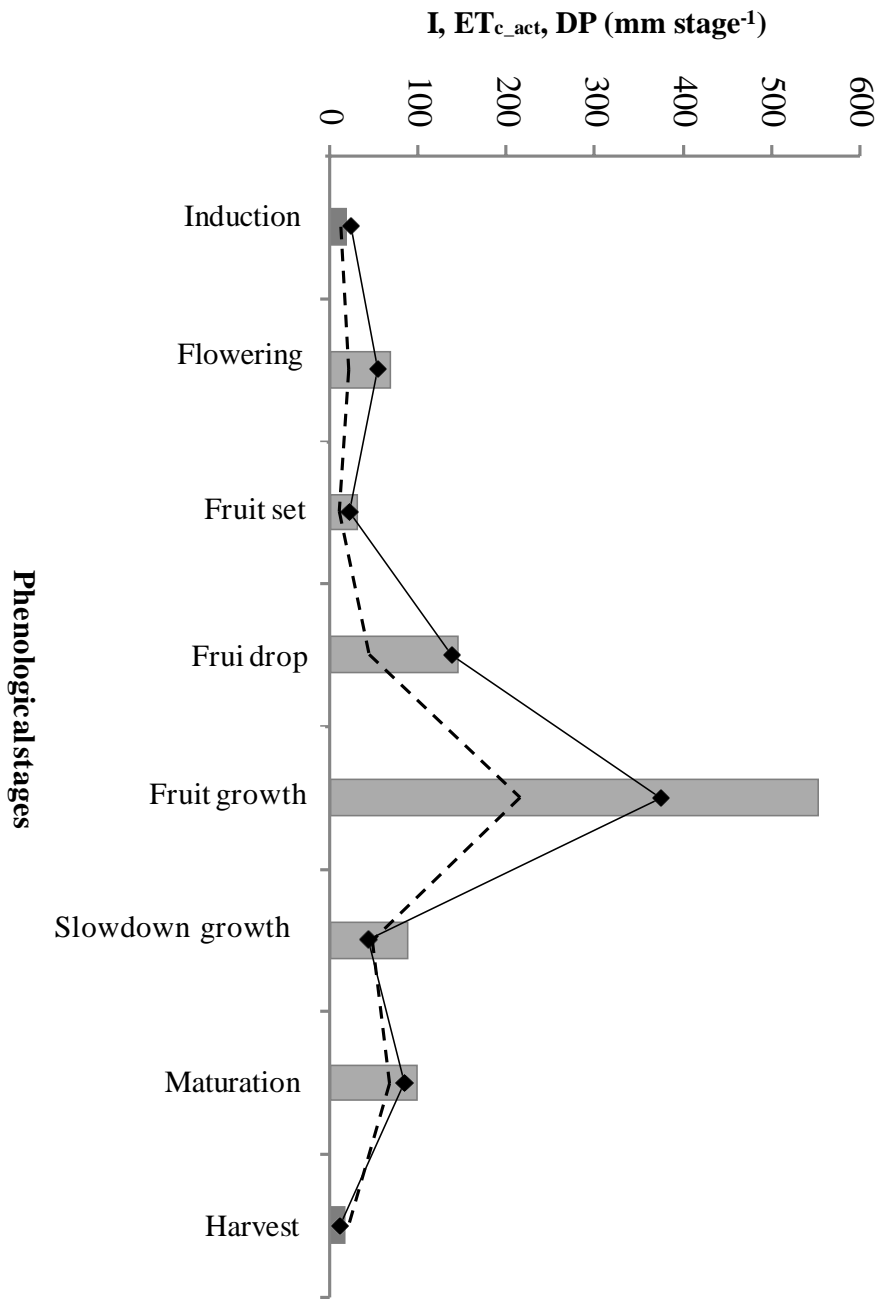


Figure 6

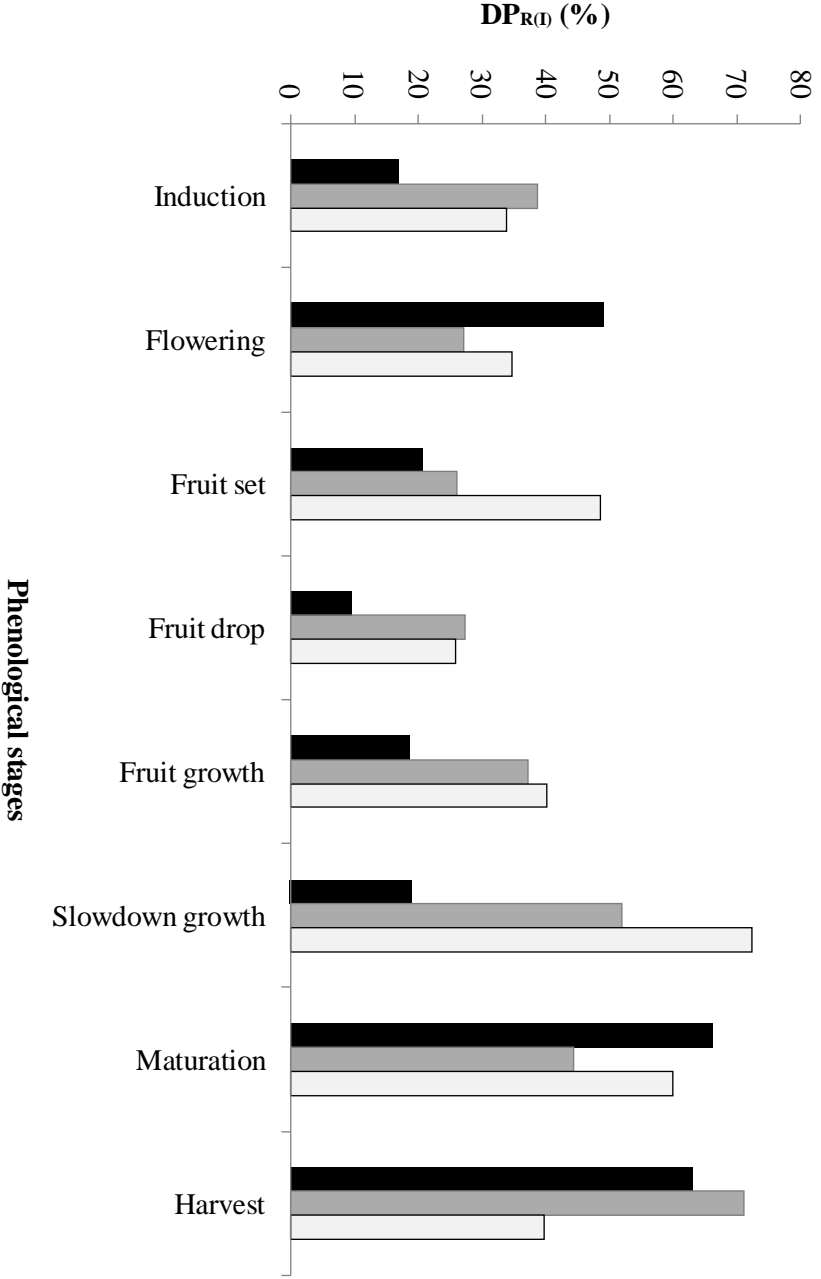


Figure 7

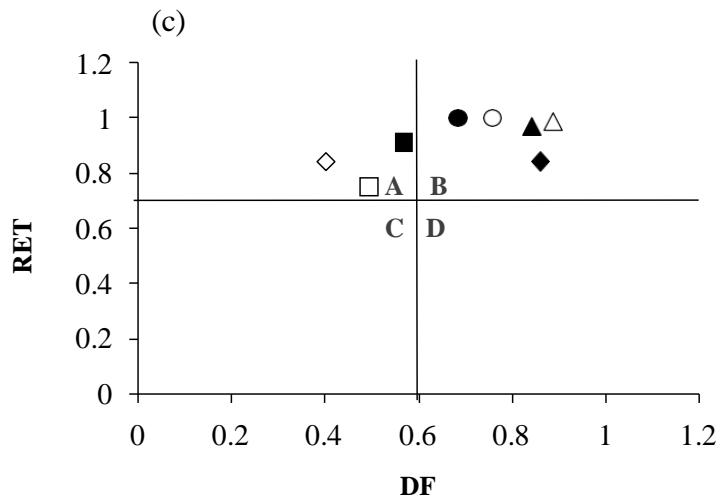
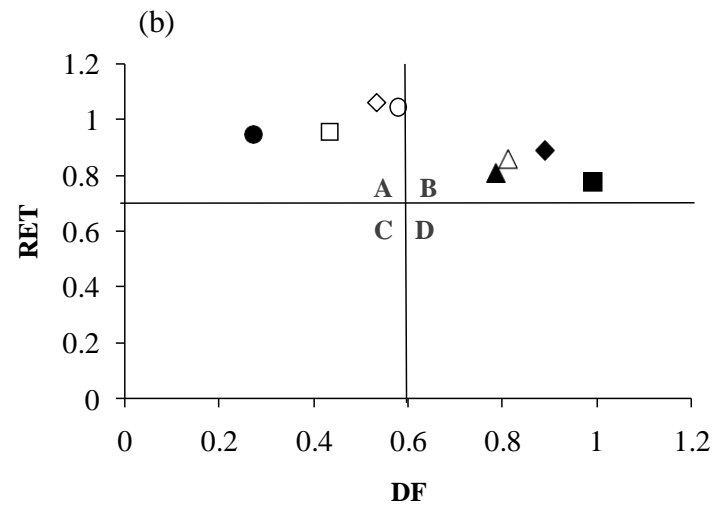
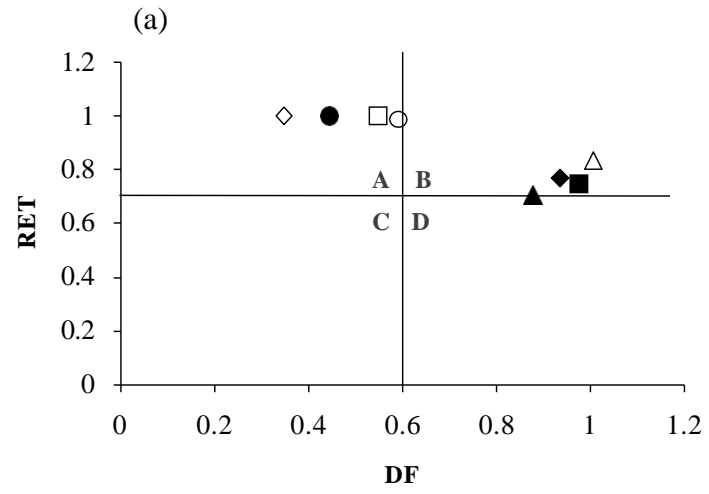


Figure 8

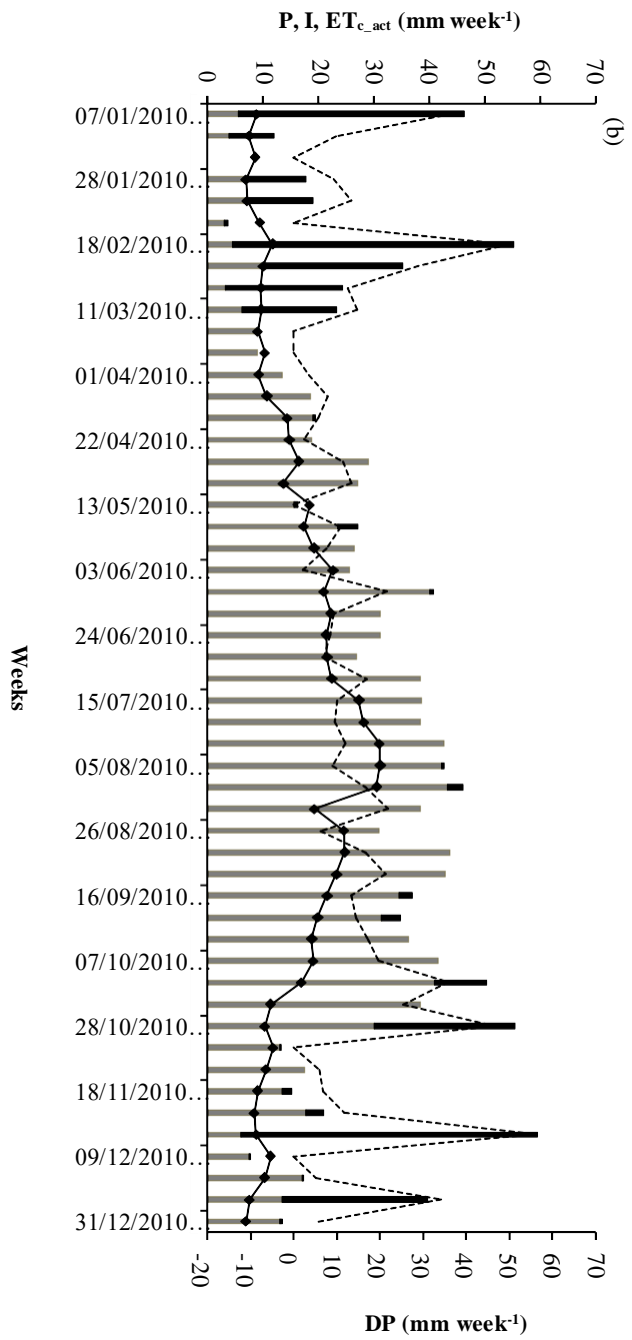
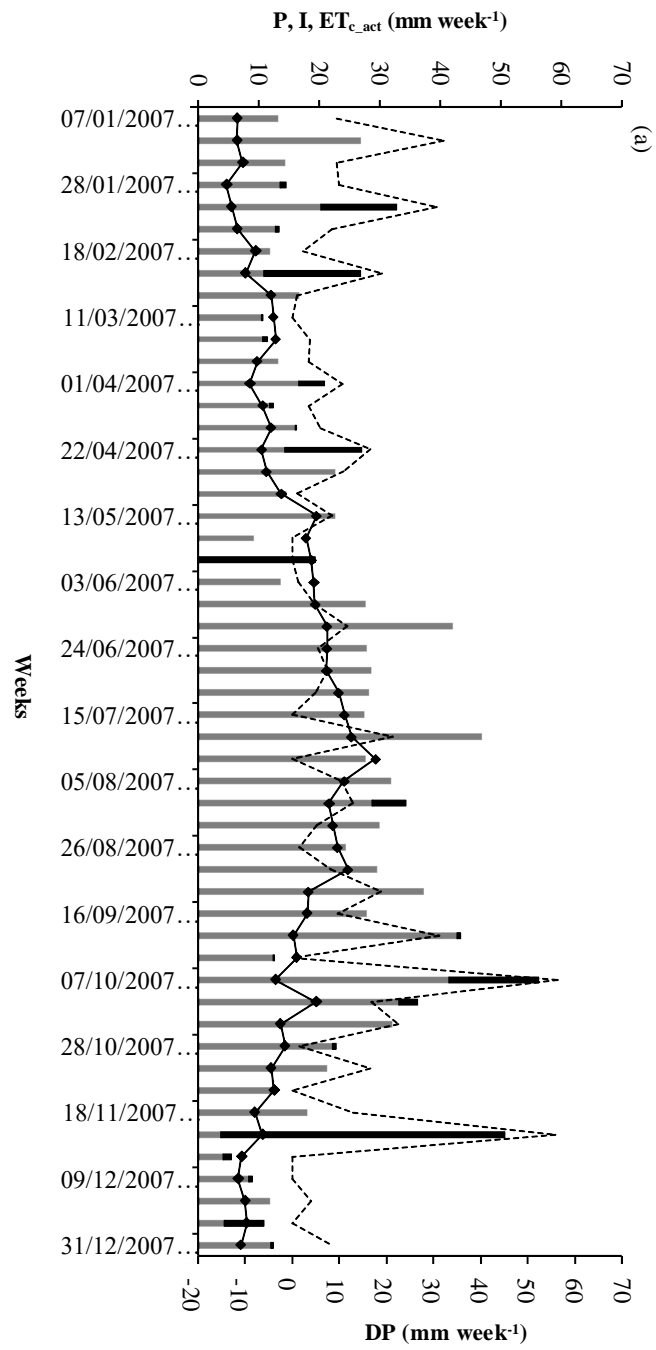


Figure 9

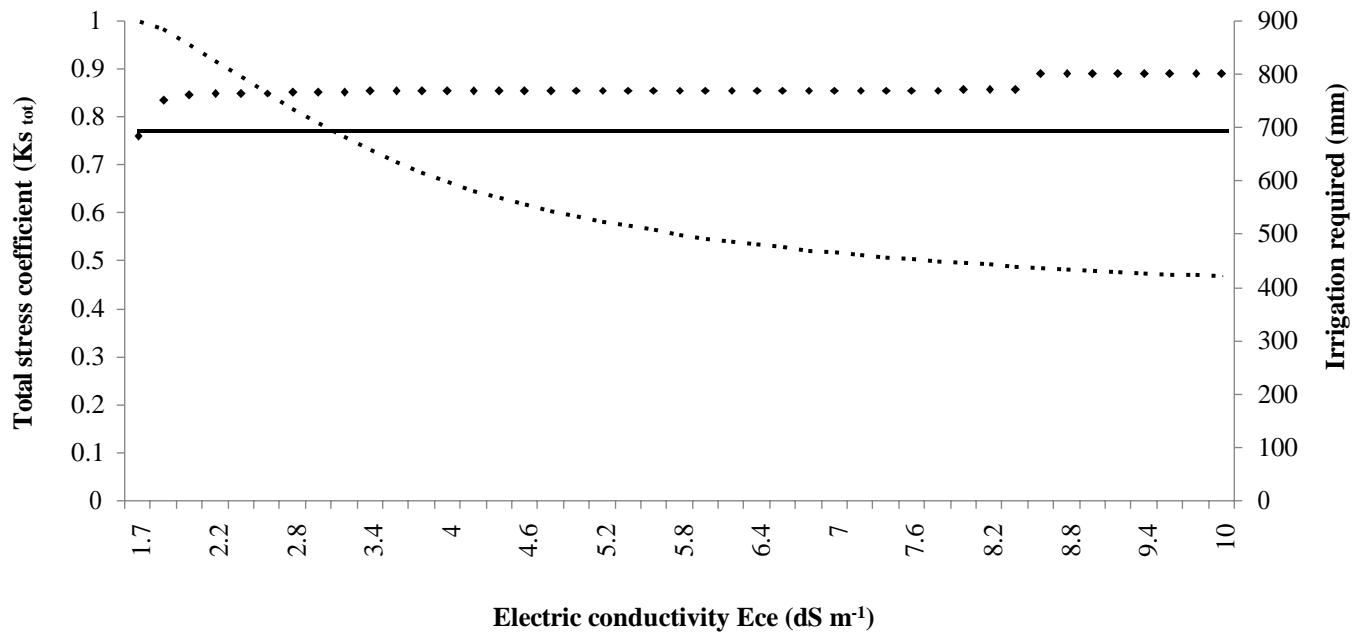


Figure 10

Table 1: Annual values of actual crop evapotranspiration ($ET_{c,act}$), rainfall (P), Irrigation (I), deep 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

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

Table 2: Seasonal values of irrigation (I), deep percolation (DP) and relative deep percolation (DP_R) in 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

Table 3: Weekly rates of irrigation (I), actual crop evapotranspiration ($ET_{c,act}$), deep percolation (DP) and 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