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Compensatory uptake functions in empirical macroscopic root water uptake models - Experimental and numerical analysis

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Abstract:Macroscopic empirical root water uptake (RWU) models are often used in hydrological studies to predict water dynamics through the soil-plant-atmosphere continuum. RWU in macroscopic models is highly dependent on root density distribution (RDD). Therefore, compensatory uptake mechanisms are being increasingly considered to remedy this weakness. A common formulation of compensatory functions is to relate compensatory uptake rate to the plant water-stress status. This paper examines the efficiency of such compensatory functions to reduce the sensitivity of simulated actual transpiration (T_a), drainage ($Drain_a$) and RWU patterns to RDD. The possibility to replace the compensatory RWU functions by an adequate description of RDD is also discussed. The study was based on experimental and numerical analysis of 2-dimensional soil-water dynamics of 11 maize plots, irrigated using sprinkler (Asp), subsurface drip (SDI) systems, or rainfed (RF). Soil water dynamics were simulated using a physically-based soil-water flow model coupled to a macroscopic empirical compensatory RWU model. For each plot, simulation scenarios involved crossing 6 RDD profiles with 6 compensatory levels. RDD was found to be the main factor in the determination of RWU patterns, T_a and $Drain_a$ rates, with and without the compensatory mechanism. The use of a water-tracking RDD, i.e., higher uptake intensity in expected wetter soil regions, was found a surrogate for compensatory RWU functions in surface-watering simulations (Asp and RF). However, in SDI simulations, a water-tracking RDD should be combined to a high level of compensatory uptake to satisfactorily reproduce real RWU patterns. Our results further suggest that the

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compensatory RWU process is independent of the plant stress status and should be seen as a response to heterogeneous soil-water distribution. Our results contribute to the identification of optimum parameterization of empirical RWU models as a function of watering methods.

Key words: Empirical macroscopic root water uptake models; Compensatory root water uptake; Sprinkler Irrigation; Subsurface drip irrigation.

1. Introduction

Water uptake by plant roots is a key element in the process of water transfer in the soil-plant-atmosphere continuum (Feddes et al., 2001). In croplands, it is estimated that 65% of the precipitation is returned to the atmosphere by evapotranspiration (Oki and Kanae, 2006). Hence, pertinent simulation of the root water uptake (RWU) process is of major importance for an efficient agricultural water management. However, the RWU process is complex, related to endogenous factors (i.e., genetic control), and to exogenous factors such as soil water content, nutrient content, temperature, aeration and microbial activity (e.g. Kramer and Boyer, 1995; Hodge et al., 2009).

Early experimental research to understand root behavior dates back to the end of the XIX[th] century, credited to the pioneer works of Charles and Francis Darwin (*The Power of Movement in Plants*, (Darwin, 1880), as has recently been recalled by Baluska et al. (2009). However, the first mathematical representations of RWU were undertaken some decades later by van den Honert (1948). Since then, RWU modeling is typically performed according to one of two approaches: the so-called microscopic and macroscopic approaches (e.g. Molz, 1981; Hopmans and Bristow, 2002; Feddes and Raats, 2004).

The microscopic models are physically-based. They consider water potential of both the root system and the soil in the immediate vicinity of roots, and describe thus water flow to and through individual roots analogously to Ohm's law. In contrast, the macroscopic approaches consider a lumped representation of both the roots and the soil. Although physically-based macroscopic RWU models exist in literature, which

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consider root water potential (e.g., Heinen, 2001; de Jong van Lier et al., 2008; Schneider et al., 2010; Couvreur et al., 2012), the macroscopic RWU models used in literature are typically empirical, neglecting the hydraulic properties of roots (e.g., Feddes et al., 1978; van Genuchten, 1987).

The choice of one modeling approach instead of another is context-dependent and still subject to debate (de Willigen et al., 2012): although physically based models are insightful for the comprehension of water and nutrient uptake processes at the root scale (Raats, 2007; Subbaiah, 2011) and require less calibration (Homaee et al., 2002), their use is still limited in the domain of crop management due to the rich parameterization and computational requirements of such models (Feddes and Raats, 2004; Subbaiah, 2011), compared to the less demanding empirical macroscopic models (Feddes and Raats, 2004; Raats, 2007; Subbaiah, 2011), designated as more “Hydrologically-oriented” (Feddes and Raats, 2004).

When integrated in a greater physically-based soil water transfer model, the macroscopic RWU models conceptualize RWU by a sink term in the Richards equation:

$$\partial\theta/\partial t=\nabla[k(h)\nabla H]-S \quad (1)$$

where θ denotes the volumetric soil water content [L^3L^{-3}], t the time [T], h the soil pressure head [L], H the soil total head [L], k the hydraulic conductivity of the soil [$L\ T^{-1}$] and S the sink term representing RWU [$L^3L^{-3}T^{-1}$]. The sink term S represents herein the actual RWU, associating the potential transpiration (T_p) to a potential root uptake distribution function (β) and to an uptake reduction function (γ) in a product formula:

$$S=T_p\gamma\beta \quad (2)$$

The function β is typically taken in literature as the bulk root density distribution (Hopmans and Bristow, 2002), and will be considered as such in this study.

Due to their simplifying assumptions, the empirical models have often been said to have little biophysical basis (Skaggs et al., 2006, Javaux et al., 2008, Schneider et al., 2010). Probably, the most important shortcoming in this type of model is the

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assumption that root activity is proportional to root density and to local water-content status through the aforementioned product formula. When described as such, RWU is represented as a passive process, i.e. uptake rates are controlled solely by climatic demand, the spatial distribution of soil water availability and root density.

In fact, it has been shown experimentally and numerically that the spatial distribution of instantaneous RWU rates may differ strongly from that of root density (Bruckler et al., 2004; Hodge, 2004, Faria et al., 2010). Such differences are expected to be greater in heterogeneous soil structures (Kuhlmann et al., 2012) and to further increase with time (Schneider et al., 2010). In addition, it has widely been shown experimentally that plants adjust their water uptake patterns to cope with soil water content distribution by an enhanced “compensatory” uptake from wetter soil regions (e.g., Green and Clothier, 1995; Hodge, 2004; Leib et al., 2006). Skaggs et al. (2006) suggested that the compensatory RWU mechanism plays a major role in simulations of soil water transfer where irrigation methods impose non-uniform water deficits in the root zone. Moreover, Kuhlmann et al. (2012) suggested that omitting the compensatory uptake may lead to underestimate plant transpiration in heterogeneous soils.

Attempts to conceptualize compensatory RWU in the empirical macroscopic models were first undertaken by Jarvis (1989) who explicitly considered a compensatory RWU function, multiplied by both γ and β functions. The author related the compensatory uptake mechanism to the plant stress index, expressed by the ratio of the actual to potential transpiration (T_a/T_p). Compensatory uptake is thus triggered in a manner that transpiration is maintained at its potential level as long as T_a/T_p is greater than a predefined threshold (ω_c). Pang and Letey (1998) also explicitly accounted for the compensatory RWU, where plant transpiration is maintained at its potential level as long as there is at least one soil region where water content is greater than a given stress threshold.

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Other compensatory RWU models in literature do not involve the T_a/T_p ratio threshold, i.e., continuous. Bouten et al. (1992), Lai and Katul. (2000) and Li et al. (2001) proposed that water uptake is proportional to both β and a weighted stress index relating the local (considered soil element) to the bulk average (entire root zone) water condition, regardless of the ratio T_a/T_p. Adiku et al. (2000) and van Wijk and Bouten (2001) considered that RWU pattern from the soil is automatically adjusted to minimize energy expenditure by the plant. Finally, water-tracking RWU models (Coelho and Or, 1996; 1999), which attribute higher uptake intensity to wetter soil regions, may provide an alternative method to implicitly account for the compensatory RWU process as proposed by Mailhol et al. (2011). However, the latter method has not been fully investigated in literature, and most studies account for the compensatory RWU via explicit functions.

The Jarvis's explicit compensatory RWU function has lately been integrated in the 2-dimensional (2D) version of the water and heat transfer model in porous media Hydrus (Simunek et al., 2008) as discussed by Simunek and Hopmans (2009). The authors suggested that the effect of the spatial root distribution on RWU may be reduced when compensatory RWU is considered, and concluded thus that a priori knowledge of the spatial root distribution may only be effective for non compensatory RWU simulations.

Despite all the attention, the Jarvis's function is perceived oversimplifying compared to microscopic modeling approach (Schneider et al., 2010; Javaux et al., 2013). Moreover, few information exists in literature on the values the ω_c threshold one should take (Skaggs et al., 2006), which often leads to use of arbitrary values (Shouse et al., 2011) or, in some cases, to abandon the use of the compensatory function (Oster et al., 2012).

Therefore, with such uncertainties in Jarvis's function parameterization, the effect of the latter on RWU pattern as evoked by Simunek and Hopmans (2009) is questionable, especially since root density distribution is well known to highly

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determine RWU pattern and rates (e.g., Beudez et al., 2013). One may wonder whether a compensatory RWU is even needed when an adequate description of root density is provided, e.g., with water-tracking RWU.

The aim of this study is to (i) examine the effects of the compensatory RWU function of Jarvis (1989), on both the rates of water outfluxes from the soil domain (transpiration and drainage) and the RWU pattern, when contrasted macroscopic root density profiles are used in combination with different compensatory levels; (ii) explore the possibility of the use of root density profiles specific to the watering method, water-tracking RWU models, as an approach to replace the need for compensatory uptake functions.

The model used for the numerical analysis is the well documented Hydrus (2D/3D) model (Simunek et al., 2008), which includes an adapted form of the Jarvis (1989) function. The simulations were performed to predict water flow in the soil for existing sprinkler-irrigated (Asp), subsurface drip-irrigated (SDI) and rainfed (RF) maize plots. The compensatory uptake levels (T_a/T_p) ranged from 1.0 (no compensatory uptake) to 0.5 (maximum compensatory level considered). Root profiles used were either hypothetical or obtained from *in-situ* root density observations. The hypothetical RDD profiles were presumed to correspond to the real root activity pattern depending of the watering method, as water-tracking RWU models.

2. Materials and Methods

Field experiments were conducted to (i) characterize *in-situ* the spatial distribution of root density of irrigated maize, (ii) monitor its vegetative development, and (iii) monitor the temporal evolution of soil volumetric water content (θ) profiles. These data were needed as input and verification of the numerical analysis. The description of the field experiments and the numerical analysis procedures is given in the following sections.

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2.1. Field experiments

The experiments were conducted at the Lavalette experimental station (43°40 N,3°50 E) of the Irstea research institute (formerly Cemagref), in Montpellier, SE France. Lavalette is fully equipped with a meteorological station which provides rainfall and the reference crop evapotranspiration (ET_{ref}) according to Penman (1948). The meteorological station is situated at an average distance of 100 m from the experimental plots.

The experiments were conducted in 2008, 2011 and 2012 on maize plots which were either irrigated using SDI or Asp systems, or rainfed. The driplines of the SDI plots were buried at 35 cm depth, having an emitter spacing of 30 cm and a lateral dripline spacing of 160 cm. In all 3 years, SDI plots were irrigated at levels of 70-80%ETM whereas the Asp plots were irrigated at levels of 70%ETM in 2008 and 100 and 50%ETM in each of 2011 and 2012.

All measurements were taken within defined sub-plots of a small surface (5*5 m^2) situated in the center of each experimental plot (1200 m^2) in order to eliminate border effects. Rain or sprinkler water influxes were measured by rain gauges situated next to the measurement sites. Similarly all fertilizer quantities were also controlled over the surface of the measurement plots.

2.1.1. Agronomic practices and measurements

The agronomic practices were similar in all 3 years. A dent hybrid maize variety was used in all three years of experiments (Pioneer PR33TY65 in 2008 and PR34P88 in 2011 and 2012). Sowing took place on day of year (DOY) 120 in 2008 and on DOY 110 in both years 2011 and 2012. Sowing lines were spaced by 80 cm and were directed East-West, aligned to SDI driplines.

The distance between the sowing lines and the driplines varied for each season within each measurement subplot. This distance was equal to 40, 30 and 65 cm respectively in 2008, 2011 and 2012.

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Crop water requirements were estimated based on the crop maximum evapotranspiration (ETM) approach (Allen et al., 1998). ETM was estimated on a daily basis as a function of ET_{ref} (provided by the meteorological station) and the crop coefficient (K_c) which is calculated as a function of the simulated Leaf Area Index (LAI) according to Allison et al. (1993). ETM served as a base point to estimate irrigation requirements after subtracting rainfall quantities. The total applied water replaced the full or a fraction of ETM depending on the predefined stress levels for each treatment. Cumulative rainfall and irrigation quantities are given in Figure 1.

The cumulative rainfall during the three growing seasons 2008, 2011 and 2012 totaled 233, 179 and 236 mm, respectively. Total irrigation amounts were 325 and 335 mm for fully-irrigated Asp treatments and 117 and 143 mm for the severely-stressed Asp treatments respectively in 2011 and 2012, while the mild-stressed Asp treatment received 260 mm in 2008. Finally, SDI plots were supplied by 235, 240 and 268 mm in 2008, 2011 and 2012, respectively.

Figure 1: Cumulative rainfall and irrigation quantities applied to all plots during the growing seasons 2008, 2011 and 2012.

The applied quantities of nitrogen fertilizers for post emergence were calculated based on the soil N content at the sowing date, the soil mineralization rate (0.8 kg ha^{-1} d^{-1}) during the crop cycle and the expected yield so that total N amounts were not a limiting factor for crop growth and grain production.

In each of the measurement plots, the vegetative development of maize was monitored regularly by measurements of the LAI, using LI-COR LAI-2000 Plant Canopy Analyzer LAI-meter. The measurements were performed at 5 locations in and around the measurement plots, and the mean values were then taken.

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The estimation of θ was performed using the neutron scattering method (CPN 503 DR, Campbell Pacific Nuclear Corp., Concord, CA, USA). The neutron probe was calibrated based on gravimetric soil water content and bulk density measurements performed on soil samples collected prior to each crop cycle from 4 soil layers (0-30, 30-60, 60-90 and 90-120 cm). Probe-access tubes were installed vertically in a maize row in each measurement plot. Some plots had an additional tube installed at mid-distance between two crop rows. Measurements were taken in most cases to a maximum depth of 200 cm, at 10 cm interval.

Further information in agronomic practices may be found in (Mubarak et al., 2009a,b) and (Mailhol et al., 2011).

2.1.2. Root density observations

The aim of the *in-situ* characterization of root density was to (i) show experimentally whether the spatial distribution of root density (RDD) may be related to the watering method and (ii) to use the resulting RDD profiles in the numerical analysis.

Root density was characterized in 2008 and 2011 at the end of the maize cycle. The data collected in both years were further enriched by data collected by former similar works performed at the Lavalette station, available from its database. In all cases, the simple method of Tardieu and Manichon, (1986) was applied (e.g., Mubarak et al., 2009a). According to this method, soil pits (about 2.0 m long, 1.0 m wide and 1.8 m deep) were excavated at the harvest of each experimental campaign, perpendicularly to the maize rows. The faces of the pits were vertical planes, subdivided in square cells (5*5 cm). Root density was assessed based on visual observation. A number ranging from 0 to 5 was assigned to each cell according to the visually observed density in a 1 cm layer of the exposed soil surface.

Figure 2 shows the observed RDD profiles for Asp (A, B and C) and SDI (D, E, F, and G) plots (only 4 SDI profiles are illustrated for the sake of visibility).

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Figure 3A shows the mean vertical RDD (the means of each horizontal line) for both irrigation methods, whereas the mean horizontal RDD (the means of each vertical line) is shown in Figure 3B for Asp and Figure 3C for SDI plots.

Figure 2: Observed root density profiles of Asp (A, B, C) and SDI (D, E, F, G) maize plots. The driplines are presented by filled black circles. Root density was evaluated visually following the method of Tardieu et al. (1986). The observed profiles come from different experimental campaigns as denoted for each profile.

Figure 3: The mean horizontal root density distribution (A) for both Asp and SDI maize plots, and the mean vertical root density of Asp (B) and SDI (C).

Since the root profiles are reconstructed from visual observations, the density indices are prone to the subjective evaluation made by the different observers and therefore these data are rather qualitative.

Roots were found to occupy the entire soil domain under maize rows and in the inter-row space, for both irrigation methods (Figure 2). Only a small decrease in root density was observed as the horizontal distance from the crop row increases (Figure 3B and C). Moreover, both Asp and SDI methods result in similar vertical RDD, with slightly higher density values for Asp in the upper 40 cm soil layer (Figure 3A). Furthermore, an interesting indication appears in Figure 2 for the SDI maize profiles: root density seems independent of the irrigation method, since no systematic increase in root density was observed in the vicinity of the drippers (represented by a blue circle), even for the same plot (Figure 2E).

The aforementioned observations do not plead in favor of the use of RDD profiles that are specific to a watering method. The results suggest that a 2D RDD profile where the root density decreases linearly, in both vertical and horizontal directions, adequately describes root systems (and consequently the potential RWU pattern) for both Asp and SDI systems. This observed RDD profile, denoted β_{Obs}, was used in the

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numerical analysis with 5 additional hypothetical RDD profiles as will be further described in section 2.3.

2.2. Numerical analysis

2.2.1. Water flow simulation model

The Hydrus (2D/3D) model was used to simulate water flow in the soil by a numerical solution to the Richards equation (Richards, 1931) supplemented with a term S to account for root water uptake. To reduce the number of the spatial dimensions from three to two, it is assumed that water flow occurs only in a vertical plane perpendicular to the crop rows. This assumption stands for sprinkler irrigation as long as water application is uniform over the soil surface in the row direction. For SDI, it is assumed that water bulbs formed by the emitters overlap and merge forming a continuous cylindrical wetted zone along the dripline rendering thus water flow a 2D problem (Lafolie et al., 1989).

Considering the aforementioned assumptions and considering the soil to be isotropic, the equation describing the flow in a vertical plane is:

$$\partial\theta/\partial t=\partial\left(\frac{k(h,z)\partial h}{\partial x}\right)/\partial x+\partial\left(\frac{k(h,z)\partial h}{\partial z}\right)/\partial z-\partial k(h,z)/\partial z-S \quad (3)$$

where x and z are respectively the horizontal and vertical (positive upwards) Cartesian coordinates [L]. The macroscopic RWU sink term S is given by:

$$S=T_p\gamma(h)\beta(x,z)\varphi \quad (4)$$

where T_p [L T-1] is the potential transpiration, γ(h) is the transpiration reduction function [-], β(x,z) is the potential RWU pattern which is identical to root density distribution RDD [L L-2], and finally ϕ is the compensatory uptake function of Jarvis (1989):

$$\varphi=\begin{cases}1/\omega;\ \omega\geq\omega_c\\1/\omega_c;\ \omega<\omega_c\end{cases} \quad (5)$$

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where ω is the plant stress index (T_a/T_p) and ω_c is a critical stress index threshold (see Jarvis, 1989 and Simunek and Hopmans, 2009 for details).

In the present study, the piece-wise stress-response reduction function of Feddes et al. (1978) was used:

$$\gamma = \begin{cases} 0; & h \geq h_1 \\ (h_1 - h)/(h_1 - h_2); & h_1 > h \geq h_2 \\ 1; & h_2 > h \geq h_3 \\ (h - h_4)/(h_3 - h_4); & h_3 > h \geq h_4 \\ 0; & h_4 > h \end{cases} \qquad (6)$$

The values of h_2 and h_3 represent the thresholds between which water uptake is assumed maximum, while h_1 and h_4 represent respectively the thresholds of oxygen deficiency due to soil saturation and the minimum soil water content observed in the core of the root system (generally close to the wilting point). The values of h_1, h_2 and h_4 were taken equal to -15, -30 and -15000 cm, respectively. Feddes et al. (1978) suggested that the value of h_3 depend on the transpiration rate. h_3 is therefore assumed to decrease as the transpiration rate decreases. Thus, h_3 was taken equal to -325 and -600 cm for transpiration rates of 5 and 1 cm day^{-1}, respectively. The parameters values of the Feddes et al. (1978) function were fixed for all simulations.

Finally, the actual transpiration is calculated as the integral of S over the root zone (Ω_R):

$$T_a = T_p \int_{\Omega_R} \gamma(h) \beta(x,z) \varphi \, d\Omega_R \qquad (7)$$

The different normalized root density distribution functions β(x,z) used in the present study will be detailed in subsection 2.3.

2.2.2. Soil domain characteristics

The width of the soil domain was set so that a zero horizontal flux Neuman-type boundary condition (BC) may be assumed across the lateral vertical boundary

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elements (Figure 4). The soil domain was thus centered over a crop row, and the soil surface width was taken equal to the spacing between two maize rows (80 cm) in Asp and RF plots. The width of SDI plots was taken equal to the half of the distance between two drip lines, assuming that a zero horizontal flux occurs on both verticals under the dripline, and at mid-distance between two driplines.

Figure 4: The geometry and boundary conditions (BC's) imposed to the soil domains with dimensions given in cm. Γ_1 is a zero horizontal flux BC, Γ_2 is an atmospheric BC, Γ_3 is a constant water-content BC and Γ_4 is a variable flux BC. The horizontal pink line at 120 cm represents the maximum root depth at which drainage was calculated.

The depth of the soil domain was set so that a Dirichlet-type constant soil-water content BC may be considered at the lower soil boundary. The depth at which changes in the value of θ were negligible was approximately 190 cm for most treatments. Therefore, the maximum depth of the soil domain was set to 200 cm.

Finally, on the soil surface, an atmospheric variable fluxes BC was imposed. All atmospheric fluxes were assumed to be uniformly distributed over the soil surface. While daily rainfall fluxes where readily available from meteorological station records, the daily potential fluxes of crop transpiration T_p and soil evaporation E_p had to be calculated from the daily ETM, using an external crop model.

The Pilote model (Mailhol., 1997; Mailhol et al., 2011) was used to separate ETM into T_p and E_p, as a function of the LAI according to Ritchie (1972) and Novak (1981). This model has been shown to yield good predictions of soil-water reserves, LAI and biomass production of maize crop in the pedo-climatic context of the Lavalette station, for surface irrigated plots, subsurface irrigated plots (Mailhol et al., 2011), both for tillage and no tillage practices (Khaledian et al., 2009). Pilote is a one dimensional bucket-type model. This model assumes the soil domain to be homogeneous and isotropic over the entire root zone, and the crop water use to be optimum as long as the lumped soil-water reserve of the root zone is greater or equal to the readily

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available water. Therefore, Pilote is root density-independent and the resulting T_p and E_p fluxes of each plot may be used in Hydrus (2D/3D) simulations regardless of the β profiles used.

Finally, the vertical soil profile of the Lavalette station shows 3 layers distinguished with specific hydrodynamic properties. Mubarak et al. (2009a) fitted soil hydrodynamic parameters to the van Genuchten-Mualem model (van Genuchten, 1980; Mualem, 1976), as described in Table 1.

Table 1: The hydrodynamic parameters of the van Genuchten-Mualem model (van Genuchten, 1980; Mualem, 1976) model fitted to the soil of Lavalette station. θ_r and θ_s denote respectively the residual and saturated volumetric soil water contents, α and n are empirical shape parameters, Ks is the soil hydraulic conductivity at saturation and l is a pore connectivity parameter.

2.3. Scenarios

To summarize:

The Hydrus (2D/3D) model was run for the simulation of water flow in the soil of 11 treatments cultivated with maize:

- AspETM (11) and AspETM (12): sprinkler, fully-irrigated treatments in 2011 and 2012,
- Asp70ETM (08), Asp50ETM (11) and Asp50ETM (12): sprinkler, deficit-irrigated treatments (30% deficit in 2008 and 50% deficit in both 2011 and 2012),
- SDI (08), SDI (11) and SDI (12): SDI, deficit-irrigated treatments (30% deficit in all 3 years),
- RF (08), RF (11) and RF (12): rainfed treatments in 2008, 2011 and 2012.

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For each of the 11 treatments, water flow was simulated for 36 scenarios (6 β profiles and 6 ω_c levels). The levels of ω_c ranged from 0.5 (the maximum compensatory uptake level considered) to 1.0 (non-compensatory uptake). The 6 β profiles are illustrated in Figure 5:

1. The "observed" RDD profile (β_{Obs}): root density decreases linearly in both the vertical and horizontal directions, as discussed in section 2.1.2.

2. The "sprinkler-specific" profile (β_{Asp}): root density decreases exponentially in both the vertical and horizontal directions. This profile was constructed using the Vrugt et al. (2001) function, implemented in the Hydrus (2D/3D) model. We hypothesize by using this profile that root activity is mainly concentrated in the shallow soil layers since irrigation is applied at the soil surface.

3. and 4. Two "SDI-specific" profiles, respectively β_{SDI-1} and β_{SDI-2}: the maximum root density is located in the vicinity of the dripper (β_{SDI-1}) or at the same depth of the dripper on the vertical of the plant row (β_{SDI-2}). Those two profiles were selected to correspond to match the cases were root density was observed to increase near the drippers (Figure 2F, G). We hypothesize thus that uptake activity of the roots mainly takes place at deeper layers as a response to the subsurface allocation of irrigation water.

5. A constant root density profile (β_{Cst}): one may suggest that β_{Cst} represents an average profile that may be used in the case were an *a-priori* knowledge of the real root density is missing, as suggested by Kandelous et al. (2012).

6. Finally, a profile of increasing root density with depth (β_{Inc}) was added. β_{Inc} is horizontally constant but increases linearly with depth. Although β_{Inc} is in total contradiction with the observations of root systems of most biomes (Schenk and Jackson, 2002), one may hypothesize that such profile may reflect an increase uptake

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activity of deep roots as soil surface dries out (e.g., Klepper, 1991). The addition of this profile aimed principally to maximize the contrast in the examined RDD profiles.

Figure 5: Root density profiles of fully-developed maize irrigated with SDI with driplines located on the right-side boundary at a depth of 40 cm. X^* and Z^* are the horizontal and vertical coordinates at which the root density is maximum. X_{max} and Z_{max} delimit the soil region occupied by roots. P_x and P_z are empirical shape parameters (specific to the function of Vrugt et al. (2001).

The numerical scheme of the simulations for each of the 11 treatments is shown in Figure 5. Since Hydrus (2D/3D) does not simulate the increase of root depth with time, a series of simulations had to be put end-to-end for each treatment, where the Z_{max} was assumed to be constant within the period of each simulation. Z_{max} values were fixed to 30, 45, 75, 105 and 120 cm. The corresponding periods of the growth cycle were given by Pilote which simulates the increase of Z_{max} as a function of the cumulative degree-day temperatures. This temporal delimitation increased the number of the simulations to total 1980 (11 treatments * 6 β * 6 ω_c * 5 end-to-end sequences). However, through all the simulated period, drainage was calculated at the depth of 120 cm, beyond which root density is assumed to become negligible.

Finally, for each of the simulations, the initial conditions were either predefined by observed θ profiles during the first growth period with Z_{max} equal to 30 cm, or read from the final time step of the previous simulation. On a personal computer (2.40 GHz processor, 32-bits, 4.00 GB RAM), the run of all simulations took approximately 24 hours.

Figure 6: Flowchart of the simulations conducted using Hydrus (2D/3D).

2.4. Statistical analysis of the results

For each treatment, observed and simulated θ profiles (θ_{obs} and θ_{sim}, respectively) were compared in order to determine the optimum simulation configuration (the choice of β profile and ω_c levels). The statistics adopted for the comparison were the

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correlation coefficient of Pearson (ρ) and the root-mean-square error (RMSE). In this context, the errors were only different from zero when θ_{sim} fell outside the associated confidence intervals (CI) of the measurements of θ_{obs} determined by the instrument and calibration curves.

Both ρ and RMSE are complementary measures. The Pearson's ρ describes the linear relationship between two continuous random variables regardless of their values. Therefore, a high value of ρ means that a strong correlation between θ_{obs} and θ_{sim} exists, indicating thus that water distribution pattern is reasonably simulated (parallel θ profiles). However, this does not mean that both simulated and observed profiles are close, hence the need for an estimate of the error by means of RMSE. To determine whether the obtained RMSE values differed significantly following values of β and ω_c statisticall tests have to be performed. In this respect, as it was found that errors $\{\varepsilon\} = \{|\theta_{obs} - \theta_{sim} - CI|\}$ increased with depth, their statistical distribution was biased and did not adhere to normality. Therefore, the statistical analyses of RMSE results was performed using nonparametric tests. Firstly, the Kruskal-Wallis (K-W) test was used to determine whether β had a significant effect on ε for each ω_c value. Secondly, when the results of the K-W test indicated a significant effect of β, the post-hoc test of Dwass-Steel-Critchlow-Fligner pair-wise test was performed to determine the significance of differences among the results.

3. Results

3.1. Transpiration

The results of the simulated transpiration fluxes are illustrated in Figure 7 for selected treatments of each watering method. In order to increase the readability of the results, the cumulative transpiration curves ($T_{a\ cum}$) are illustrated only for the non compensatory (ω_c = 1.0) and the maximum compensatory (ω_c = 0.5) RWU levels. The corresponding differences in $T_{a\ cum}$ [mm] between those two latter cases are summarized in Table 2.

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Figure 7: The cumulative transpiration curves $T_{a\ cum}$ simulated with non compensatory (left column) and the maximum compensatory (right column) RWU levels.

Table 2: The differences between the maximum and the minimum simulated cumulative transpiration Ta cum for each treatment, using all β profiles (columns 2 to 5) and only those of the "realistic" group (columns 6 to 9).

Surface-watering simulations

In sprinkler treatments, using contrasted β profiles resulted in differences in $T_{a\ cum}$ within the range of 22 to 63 mm, representing respectively 4.5% and 14.0% (1-min/max %) as shown in Table 2 (columns 2 and 3). These differences were higher for fully-irrigated treatments than for those deficit-irrigated. However, for all irrigation levels, the simulation with the maximum compensatory RWU level considerably reduced the effect of β, to produce, in the cases of AspETM (12) and Asp70ETM (08), almost identical total $T_{a\ cum}$ values (Table 2, columns 4 and 5).

Similar results were obtained for rainfed treatments, even though the simulated $T_{a\ cum}$ showed a higher sensitivity to β. Contrasted β resulted in higher differences in $T_{a\ cum}$, ranging from 28 to 87 mm which represent respectively 15.4% and 34.1% (Table 2, columns 2 and 3). These differences were considerably reduced to about 13% for all treatments when the compensatory RWU was activated (Table 2, columns 4 and 5).

The aforementioned differences in $T_{a\ cum}$ come principally from β_{Cst} and β_{Inv}. When the latter are not considered, the simulated differences in $T_{a\ cum}$ become considerably lower (Table 2, columns 6 to 9). The profiles β_{Asp}, β_{Obs}, β_{SDI-1} and β_{SDI-2} resulted in very similar transpiration rates even when no compensatory RWU was considered. The corresponding differences between $T_{a\ cum}$ maxima and minima were then between 2.0 and 7.5%, but in absolute water depth terms were all smaller than 16 mm.

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The results of surface-watering simulations are not very sensitive to the spatial distribution of root density RDD, provided that the latter decreases linearly or exponentially with depth as observed for most realistic plant biomes by Schenk and Jackson (2002). In this case, considering compensatory RWU yielded only a limited effect on the simulated $T_{a\ cum}$, where the differences between $T_{a\ cum}$ minima and maxima were all reduced by less than 13 mm (Table 2, columns 8 and 9), except for the case of RF (11) where those differences were increased using the compensatory uptake function.

SDI simulations

Root density distribution played a greater role in the determination of transpiration rates in SDI treatments.

Considering for instance only β profiles of the "realistic" group (β_{Asp}, β_{Obs}, β_{SDI-1}, β_{SDI-2}): β_{Asp} and β_{SDI-1} systematically resulted in the lowest and the highest transpiration rates, respectively (SDI results in Figure 7, left column). For non compensatory water uptake, the differences between $T_{a\ cum}$ maxima and minima ranged from 37 mm (9.2%) for the case of SDI (11) to as much as 83 mm (21.1%) for that of SDI (12), (Table 2, columns 2 and 3). This greater difference obtained in 2012 was due to the higher plant-dripline distance (65 cm) compared to 2008 and 2011 (40 and 30 cm, respectively). Consequently, β profiles with maximum root densities located beneath the plant row resulted in considerably lower water uptake compared to β_{SDI-1}.

However, activating the compensatory RWU function considerably reduced the differences between $T_{a\ cum}$ maxima and minima, but this decrease strongly depended on the plant-dripline distance. While those differences were reduced by 27 mm in both 2008 and 2011 (62% and 72%, respectively), the compensatory uptake resulted in a limited reduction of only 12 mm (15%) in $T_{a\ cum}$ (max-min) in the case of 2012 (Table 2, column 6 compared to column 8). Furthermore, for the case of 2012, more enhanced transpiration was simulated with β_{Obs} profile than with that of β_{SDI-2} since the latter had less root density in the vicinity of the dripper compared to β_{Asp}.

3.2. Drainage

Similar to the previous section, the simulated drainage outfluxes below the root zone (Z = 120 cm) are illustrated only for a selected number of treatments (Figure 8). The differences in the cumulative drainage outfluxes ($Drain_{cum}$) are summarized in Table 3.

Figure 8: Cumulative drainage/capillary rise outfluxes simulated with non compensatory (left column) and the maximum compensatory (right column) RWU levels. Vertical bars represent rainfall and irrigation events.

Table 3: The differences between the maximum and the minimum simulated cumulative drainage $Drain_{cum}$ outfluxes for each treatments, using all β profiles (columns 2 and 3) and only those of the "realistic" group (columns 4 and 5).

Globally, the cumulative drainage outfluxes or capillary rise influxes followed the vertical distribution of root density, i.e. root profiles with higher root densities in lower soil layers resulted in systematically lower drainage rates or higher capillary rise (Figure 8). The simulations using β_{Inv} resulted in systematically the highest capillary rise rates, followed by the simulations issued from the β_{Cst}, then those of β_{SDI-1} and β_{SDI-2} (both being quasi-identical for all sprinkler and rainfed simulations), then β_{Obs} and β_{Asp} last.

Surface-watering simulations

Two groups of $Drain_{cum}$ curves are clearly distinguished in Figure 8: those resulting from the "realistic" (β_{Asp}, β_{Obs}, β_{SDI-1} and β_{SDI-2}) and those from the "atypical" (β_{Cst} and β_{Inv}) profiles.

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The compensatory uptake had a limited effect on $Drain_{cum}$ (Table 3): it reduced $Drain_{cum}$ by less than 6 mm in all simulations of the surface-watering treatments, but failed to reduce differences of $Drain_{cum}$ (max-min). The latter were merely the same with and without compensatory uptake. These results indicate that, in the case of surface-watering conditions, the effect of the compensatory RWU function on the reduction of the sensitivity of the simulated drainage is negligible.

SDI simulations

The sensitivity of drainage prediction to the spatial distribution of root density was considerably higher under SDI conditions, as may be seen from Figure 8.

In addition to the vertical distribution of root density, the simulated $Drain_{cum}$ depended on the position of the plant row relative to the dripline. For instance, for similar total irrigation depths in 2008, 2011 and 2012, the lowest drainage rates were obtained with $\beta_{SDI-1}$and β_{SDI-2}, in 2008 and 2011, but not in 2012 when β_{SDI-2} resulted in considerably higher drainage outfluxes due to higher plant-dripline distance.

Compensatory RWU efficiently reduced both the absolute value of drainage outfluxes and the relative differences resulting from the contrasted β profiles (Table 3 columns 3 and 5 compared to columns 2 and 4, respectively). The plant-dripline distance also conditioned the efficiency of the compensatory uptake function. The reduction rates were greater with smaller plant-dripline distance : the simulated $Drain_{cum}$ in the case of SDI (12), using β_{Asp}, was reduced by 35 mm for a ω_c of 0.5, while only a reduction of 5.3 mm was obtained in the case of SDI (11), for the same conditions (Table 3).

The compensatory uptake has thus a non negligible effect on the reduction of the sensitivity of Hydrus (2D/3D) model to the β function, when it comes to drainage simulation in SDI treatments. However, strong discrepancies in simulated drainage outfluxes were still mainly explained by the β function. One may thus suggest that, in the context of a macroscopic, empirical, RWU model as such implemented in Hydrus

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(2D/3D), reasonable predictions of drainage outfluxes may require the use of β profiles that are watering method-specific (water-tracking). This hypothesis is verified by the comparison of the observed θ profiles to those simulated, describing the RWU patterns.

3.3. RWU patterns

The values of Pearson correlation coefficient (ρ) between θ_{obs} and θ_{sim} for all scenarios are shown in Figure 9.

Figure 9: Correlation coefficient of Pearson (ρ) between θ_{obs} and θ_{sim} profiles for all scenarios. Only the positive ρ values are shown.

Three main points are drawn from the results of the correlation test:

1. The compensatory RWU process does not have a systematic effect on the improvement of the predictions of RWU patterns: only the cases of AspETM (11) and SDI (08) showed an increased value of ρ following an increase of ω_c, while for the rest of the simulations the compensatory RWU had a very limited effect on ρ.

2. For the β_{Cst} and β_{Inv} profiles, the poor values of ρ were improved with compensatory RWU, but never reached those of the other realistic profiles (β_{Asp}, β_{Obs}, β_{SDI-1} and β_{SDI-2}). This shows the limits of the efficiency of the compensatory RWU when used with a poor representation of root density.

3. Water-tracking β profiles result in the best correlations, with and without compensatory uptake: highest ρ values were obtained with β_{Asp} and β_{SDI-1} respectively in surface-watering and SDI simulations.

The effects of ω_c on ρ for each β are further examined via the RMSE values, summarized in Table 4 for the simulations of the non compensatory (a) and the compensatory (b) water uptake level of 0.5.

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Table 4: Root-mean-squared errors (RMSE) [-] between θ_{sim} and θ_{obs} profiles for non compensatory (a) and compensatory uptake (b) simulations. RMSE values followed by the same letters indicate no statistically significant differences (α = 0.5).

The results of the ρ statistic are confirmed by RMSE values: poor predictions of θ using β_{Cst} and β_{Inv} but better predictions using the β profiles of the “realistic” group. Moreover, all “realistic” profiles yielded simulations with similar RMSE values, while those of β_{Cst} and β_{Inv} resulted in significantly (α = 0.5) higher RMSE in most simulations. The lowest errors were obtained with β_{Asp} for most surface-watering treatments, while the lowest errors in SDI treatments were obtained with the β_{SDI-1} profile.

While the differences in RMSE among simulations were reduced with compensatory RWU, their absolute values were unexpectedly increased for most simulations (Table 4b compared to Table 4a). To explain this increase, it will be necessary to graphically compare θ_{sim} to θ_{obs} profiles for both compensatory and non compensatory RWU simulations. This comparison is only performed for selected cases. The reader may refer to the supplementary materials to get access to the integrity of simulation results.

Surface-watering simulations

Figure 10: Comparison between θ_{sim} and θ_{obs} for all rainfed treatments, for non and maximum compensatory RWU level. The horizontal bars represent measurement errors corresponding to the neutron probe calibration equation.

Reasonable agreements between θ_{sim} and θ_{obs} were obtained without compensatory RWU in rainfed treatments (Figure 10, rows 1, 3 and 5). Using the “realistic” β profiles resulted in predictions of θ within the observation confidence

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intervals in RF (08) and RF (11), but slightly overestimated θ in deep soil layers in RF (12). In contrast, using β_{Cst} and β_{Inv} resulted in significantly higher and lower θ values in upper and lower soil layers, respectively.

The simulation with compensatory RWU slightly improved the predictions of θ in RF (11) and RF (12), by an enhanced water uptake in deeper soil layers (Z ≥ 40 cm), (Figure 10, rows 4 and 6). However, it led to an insignificant reduction of the predicted θ values (the θ profile remained within the confidence interval of measurements) when the β_{Asp} was used in the case of RF (08), (Figure 10, row 2). This implies that the resulting increase of 59 mm (35%) in $T_{a\ cum}$ obtained with the compensatory uptake using β_{Asp} in 2008 is insignificant, and may thus be associated to the sensitivity of Hydrus (2D/3D) to the spatial distribution of root density. Moreover, in RF (08) the compensatory RWU led to significantly underestimate θ in deep soil layer, when β_{Asp} was not used. This indicates that root density distribution is the factor that mostly determine water uptake pattern, with and without the compensatory uptake function. Furthermore, these results suggest that a compensatory mechanism did not take place in the rainfed treatment of 2008, and that for rainfed treatments of 2011 and 2012, improvements in water-content predictions may have simply been achieved by modifying the parameters of the Feddes stress function (more tolerance to drought).

Similar results were obtained concerning the deficit-irrigated sprinkler treatments (data not shown), but with the compensatory function slightly improving predictions of θ in upper soil layers by an enhanced water uptake following watering. Nonetheless, this enhanced uptake activity failed to mimic water uptake pattern in the more dynamic watering conditions of the fully irrigated sprinkler treatments (AspETM 11 and AspETM 12), as shown in Figure 11.

Figure 11: Comparison between θ_{sim} and θ_{obs} for the fully-irrigated sprinkler treatments, for non and maximum compensatory RWU level. The horizontal bars represent measurement errors corresponding to the neutron probe calibration equation.

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Strong discrepancies were obtained in the fully-irrigated sprinkler treatments between all θ_{sim} and θ_{obs} (Figure 11). From mid-season (DOY 170-180), all simulated profiles showed a systematic overestimation of RWU in soil layers between 40 and 90 cm depths, and underestimated RWU in shallow soil layers. Given the reasonable estimations of plant water requirements by Pilote (Appendix A1) and the fact that irrigation and rainfall amounts were gauged directly in the vicinity of the instrumented plots; it is unlikely that those discrepancies come from errors in the estimations in either of T_a or water influxes rates.

When these discrepancies are further prone to increase with compensatory RWU (see values of RMSE in Table 4b compared to Table 4a), one may then suggest that such systematic discrepancies may only be suppressed by changing the root profile, by increasing root density in the upper layers. This hypothesis was verified by performing the simulations of both fully-irrigated treatments using a new root profile: β_{ETM}. The root density of β_{ETM} is horizontally constant, but the density index (adimensional) decreases linearly from 1.0 to 0.1 between depths of 0.0 and 30.0 cm, then decreases linearly to reach 0.0 at a depth of 120.0 cm. These simulations were only performed for two compensation levels : ω_c = 1.0 and ω_c = 0.5. The resulting θ profiles are shown in Figure 12 only for simulations using β_{Asp} and β_{ETM}.

Figure 12: Comparison between θ_{sim} and θ_{obs} for the fully-irrigated treatments. The simulations were conducted using β_{Asp} and β_{ETM} profiles, for non and maximum compensatory RWU level. The horizontal bars represent measurement errors corresponding to the neutron probe calibration equation.

Substantial improvements were obtained when β_{ETM} profile was used (Figure 12). Better agreements between θ_{sim} and θ_{obs} were achieved for both ω_c values in AspETM (12), but only for ω_c = 1.0 (non compensatory uptake) in the case of AspETM (11). In the latter case, $T_{a\ cum}$ was equal to 459 mm compared to 502 mm with compensatory

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uptake, i.e. an overestimation of 43 mm (9.4%) resulted from considering compensatory RWU.

This result confirms the former observations, in rainfed and deficit-irrigated sprinkler treatments, on the role of the β function being the main factor to determine water extraction pattern. In addition, this result points out to the possibility of an overestimation of transpiration when the compensatory uptake is considered.

SDI simulations

Due to the inherent high spatial heterogeneity of soil water-content in SDI treatments, the comparison between θ_{sim} and θ_{obs} was performed on two verticals: the first on the crop row and the second in the immediate vicinity of the dripline (Figure 13) where measures of θ were only available in 2011 and 2012.

Figure 13: Comparison between θ_{sim} and θ_{obs} under plant row and dripline for SDI (11) and SDI (12), for non and maximum compensatory RWU levels. The horizontal bars represent measurement errors corresponding to the neutron probe calibration equation.

Both β and the compensatory RWU function were determinant factors to achieve reasonable predictions of θ profiles. Best agreements between θ_{obs} and θ_{sim} were obtained under both crop row and dripline when β_{SDI-1} was used in combination with the maximum compensatory RWU level (Figures 13). An interesting observation in Figure 13 is that of SDI (12) on DOY 214 and 242, where β_{SDI-1} allowed to obtain remarkably close predictions of θ profile, despite the relatively long plant-dripline distance of 65 cm. However, in some cases the compensatory RWU resulted in significant underestimation of θ_{sim} in upper soil layers under the crop row during earlier growth stages .

The results indicate that RWU is strongly underestimated if the compensatory RWU is not considered. Moreover, even for the maximum compensatory level, RWU is underestimated if β_{SDI-1} is not used (e.g., final observation dates in Figure 13). For

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instance, for SDI (08), SDI (11) and SDI (12), using β_{Asp} instead of β_{SDI-1} underestimate plant transpiration by respectively 43, 37 and 83 mm with non compensatory RWU, or respectively by 16, 10 and 71 mm when a compensatory RWU is considered.

Due to the more dynamic pattern of water allocation in SDI treatments (by both rainfall and dripline), maximum root activity is expected to alternate between the soil regions at surface and near the dripper, an activity that a static root density profile fail to mimic. Using the compensatory RWU allowed to overcome this shortcoming of static β profiles. However, reasonable predictions of RWU activity was only achieved combining a high compensatory RWU level with a water-tracking root density profile. The latter was then found to be the determinant factor for reasonable RWU simulation in SDI treatments.

4. Discussion

4.1. The efficiency of the compensatory root water uptake function ϕ

Let us recall the definition of the compensatory RWU process as proposed in the pioneer work of Jarvis (1989): the ability of plants to compensate stress-induced reduction of water uptake in one part of the root zone by an enhanced uptake from other parts where soil water is more readily available. On the one hand, we showed that using the compensatory RWU function efficiently increased the values of ρ between observed and simulated θ profiles, indicating thus better “overall” mimicking of RWU pattern. However, on the other hand, the compensatory RWU led to larger prediction errors $\{|\theta_{obs} - \theta_{sim} - CI|\}$, which means that these errors came from enhanced water uptake in the “wrong” soil regions:

1. In surface-watering simulations, the enhanced RWU by the compensatory process took place mainly in deep soil layers. When rainfed treatments are considered, RWU was not observed to be enhanced in deep soil layers in all treatments. When fully-irrigated sprinkler treatments are considered, enhanced

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RWU was observed in the uppermost soil layers due to the surface irrigation regime.

2. In subsurface drip irrigation simulations, the enhanced RWU by the compensatory process led to obtain remarkably good agreements between $θ_{obs}$ and $θ_{sim}$ under the dripline when root density was adequately described. However, since the compensatory rate is proportional to the T_a/T_p ratio (Eq. 5) rather than soil-water content spatial distribution, the enhanced RWU was not limited to soil regions around the drip water source, but occurred in the entire root zone. Consequently, simulated enhanced RWU also occurred beneath the plant row contrarily to observations.

Points 1 and 2 indicate that the compensatory RWU process may hardly be seen as a response to the total plant stress status ratio T_a/T_p. Our results suggest that the compensatory RWU pattern depends on the distribution of water through the soil domain, rather than plant water deficit.

The results of this study are in agreement with a recent study on RWU pattern conducted by Javaux et al. (2013). Using a physically-based macroscopic RWU model developed by Couvreur et al. (2012), Javaux et al. (2013) found that the compensatory RWU rate is independent from the ratio ($ω/ω_c$). Both studies of Couvreur et al. (2012) and Javaux et al. (2013) further proposed a decoupling of the water stress function γ(h) from that of the compensatory RWU, since the latter occurred even at very low water potential levels. The compensatory RWU is thus perceived as the redistribution of RWU due to a nonuniform water head distribution at the soil–root interface.

A number of examples of empirical compensatory RWU functions which are independent from the T_a/T_p ratio exists in literature (e.g., Bouten et al., 1992; Lai and Katul., 2000; Li et al., 2001). However, such models are also shown to be highly dependent on root density (see Heinen, 2014 for the case of the function of Bouten et al., 1992), and still couple the water stress and compensatory processes. An

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interesting approach to RWU simulation would be to extrapolate the propositions of Couvreur et al. (2012) and Javaux et al. (2013) for the modeling of empirical macroscopic RWU models. Such extrapolation may replace Equation 4 for the calculation of RWU by another one of the form:

$$S = T_p \beta(x,z)\left[\gamma(h) + \varphi(h)\right] \quad (8)$$

The quantity T_p β(x,z) γ(h) in Equation 8 represents RWU in standard conditions (uniform soil water potential over the entire root zone), while the quantity T_p β(x,z) ϕ(h) represents the instantaneous adjustment of RWU distribution to cope with the variations of soil water potential in the root zone. For example, the distribution of the values of ϕ(h) may be deduced from moment analysis of the spatial distribution of soil water potential. Furthermore, analogously to the formula proposed by Couvreur et al. (2012), the sign of ϕ(h) may be positive (enhanced uptake) or negative (hydraulic lift). However, more research is needed to propose a formula for the ϕ(h) that respects the condition ($T_a \leq T_p$). Such work is beyond the scope of the present study.

4.2. The role of root density distribution

Warrick and Or (2007) stated that “often no distinction is made between root length density and root activity or uptake”. Maintaining the current formula of the RWU function (Eq. 2 and 4) implies that all roots are considered active. Therefore, β must reasonably reflect the RWU activity. Both by experimental (e.g. Homaee et al., 2002; Hodge, 2004) and numerical analysis (Bruckler et al., 2004; Faria et al., 2010), RWU activity was widely reported to employ only a limited percentage of the entire root system.

It was shown in section 3 that β has a determinant role in the prediction of RWU pattern, under all water stress conditions. It was shown in Figure 9 and Table 4 that better predictions of θ were obtained when root profiles specific to the watering method were used: β_{ETM} in fully-irrigated sprinkler treatments, β_{Asp} in deficit-irrigated sprinkler treatments and $\beta_{SDI\text{-}1}$ in SDI treatments.

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By numerical analysis with a physically-based RWU model, Bruckler et al. (2004) found that surface watering events resulted in roots having high instantaneous water uptake rates. Consequently, only a limited number of roots assured the full water requirements by plants. The results of the present study are in agreements with the findings of Bruckler et al. (2004). It was shown in section 3 that a correct prediction of RWU pattern, in fully-irrigated sprinkler treatments, was obtained if and only if a specific β profile (β_{ETM}), having the maximum root density in the uppermost soil layers, was used. In SDI treatments, reasonable prediction of RWU pattern required both a high compensatory RWU level and a root profile with maximum density near the dripper.

These results plead in favor of the use of water-tracking RWU, particularly in the case of locally-watered soil domains where a reasonable prediction of RWU pattern requires both a pertinent description of the spatial distribution of root density and a high compensatory uptake level. In that sense, when Equation 4 is used to describe RWU, the β function should not only reflect the potential RWU pattern according to root density, but also according to the expected soil-water availability (i.e., watering influx distribution). This recalls the early definitions of β as “root effectiveness function” as stated by Whisler et al. (1968). Thus, by using a watering method-specific β, the aim is to increase the probability of an enhanced water uptake in predefined wetter soil regions.

Another issue related to root density distribution is its relation to the simulated water outfluxes from the soil domain. T_a is the integral of the spatially-distributed RWU (Eq. 7). Therefore, it is expected that different root density profiles may lead to similar transpiration rates. By comparing 4 different RWU models, going from empirical macroscopic to physically-based microscopic, de Willigen et al. (2012) found that differences in total transpiration were small compared to those of the simulated soil-water dynamics. The authors explained their results by the feedback process between the RWU and water flow models. This shows that the determination of the “best” RDD

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function or compensatory RWU level based solely on comparisons to measured T_a is a condition necessary but not sufficient. This confirms the pertinence of the choice to base our analysis on the comparison between θ_{sim} and θ_{obs}, which not only allows an insight to RWU pattern, but also assures mass balance conservation ($T_{a\ cum}$).

Finally, our results showed that using a uniform β profile, when relevant information on root system is missing, may lead to poor estimates of plant transpiration and drainage fluxes as well as RWU pattern, under both surface and subsurface waterings. Such consideration may thus bias the evaluation of optimum SDI design when an inappropriate β profile is used, as performed by Kandelous et al. (2012).

4.3. The performance of the empirical macroscopic RWU approach

The empirical macroscopic RWU models are often subject to critical comments ranging from too little biophysical basis (Skaggs et al., 2006; Javaux et al., 2008; Schneider et al., 2010; Javaux et al., 2013) to too many parameters requiring calibration (Feddes et al., 2001; Homaee et al., 2002; Couvreur et al., 2012; de Willigen et al., 2012), and questionable performance in heterogeneous soils (Kuhlmann et al., 2012).

However, the results obtained in this study show a rather robust performance of this RWU approach in stratified soil profiles, under contrasted watering methods, watering dynamics and water stress status, provided that adequate descriptions of the root density distribution and compensatory levels are used. These were nonetheless the results of rather simple cases of a mono-crop cultivated soil domain, and are thus subject to vary for more complex systems, where more sophisticated physically-based models may be more efficient.

5. Conclusions

Using an empirical macroscopic root water uptake model integrated in a physically-based soil water flow model, a numerical analysis was performed to

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examine the sensitivity of simulated actual transpiration (T_a), drainage ($Drain_a$) and root water uptake (RWU) patterns to both root density distribution (RDD) and compensatory RWU functions. The numerical analysis was based on simulations of water transfer in a vertical 2D soil domain cultivated with maize, irrigated by surface (sprinkler) or subsurface (SDI) systems, or rainfed. The simulations were compared to experimental data to estimate the errors in drainage rates due to uncertainties in the RDD, to study the effect of the compensatory RWU function on the sensitivity to RDD, and to verify whether the use of a water-tracking root density profile replaces the need for compensatory RWU functions. The principal findings of this study may be summarized in the following points:

1. The simulation of T_a, showed to be of low sensitivity to RDD in sprinkler-irrigated (Asp) and rainfed (RF) treatments, provided that root density decreases linearly or exponentially with depth. In contrast, RDD played a greater role in the determination of T_a in the case of subsurface drip-irrigated (SDI) treatments.

2. The simulation of $Drain_a$ was found to vary considerably in all cases with the RDD.

3. The compensatory RWU function further reduced the sensitivity of the simulated T_a to RDD in surface-watering treatments and, to a lesser extent, in SDI treatments. The efficiency of the compensatory RWU function in SDI simulations depended on the plant-dripline distance.

4. The compensatory RWU function had low or no effect on the reduction of the sensitivity of the simulated $Drain_a$ to RDD in surface-watering treatments. In contrast, compensatory RWU function played a considerable role in the reduction of differences resulting from different RDD profiles in SDI simulations. However, reasonable predictions of the RWU pattern were only achieved when a RDD profile specific to SDI was used with a high compensatory RWU level.

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5. Using an empirical macroscopic RWU function, it was shown that the main condition for reasonable estimation of T_a, $Drain_a$ and RWU pattern was to use water-tracking RWU.

6. Finally, the results suggest that the use of the compensatory RWU function of Jarvis (1989) is recommended for simulations with local water influx simulations (SDI), but questionable performance is expected in simulations were water influx is uniform over the soil domain surface (sprinkler).

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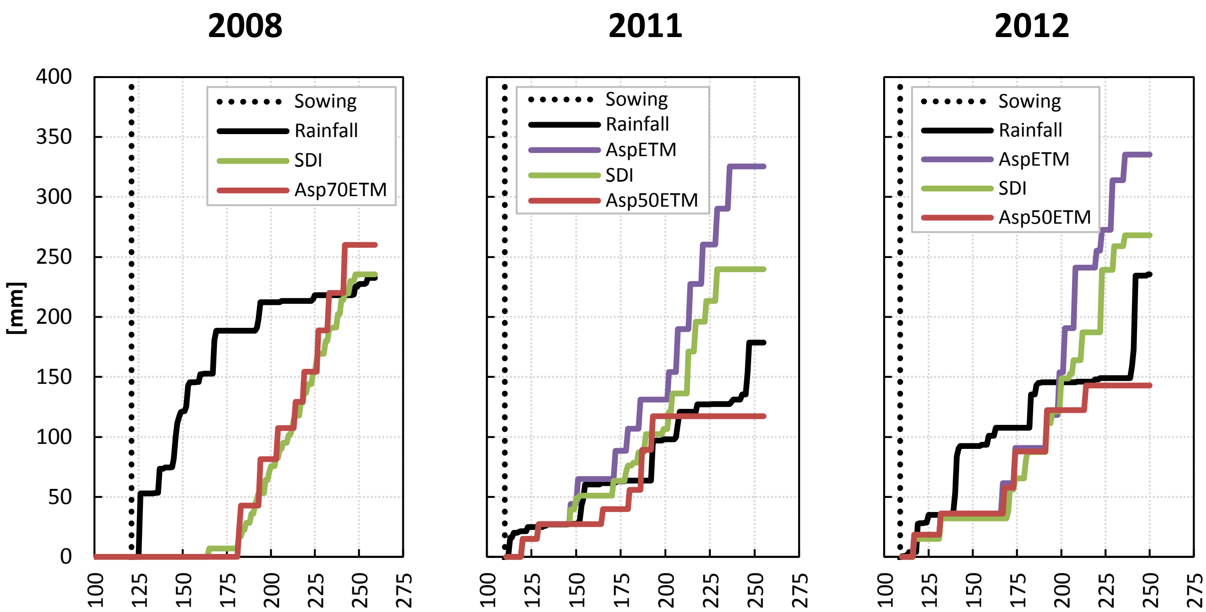

FIGURE 1 : Cumulative rainfall and irrigation quantities applied to all plots during the growing seasons 2008, 2011 and 2012.

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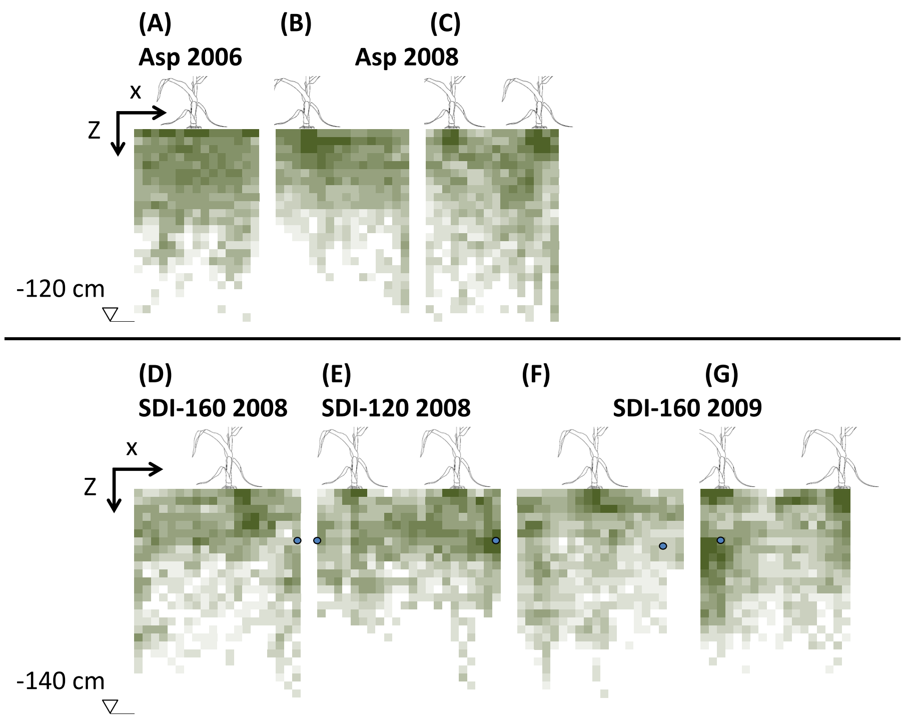

Figure 2: Observed root density profiles of Asp (A, B, C) and SDI (D, E, F, G) maize plots. Root density was evaluated visually following the method of Tardieu and Manchion (1986). The observed profiles come from different experimental campaigns as denoted for each profile.

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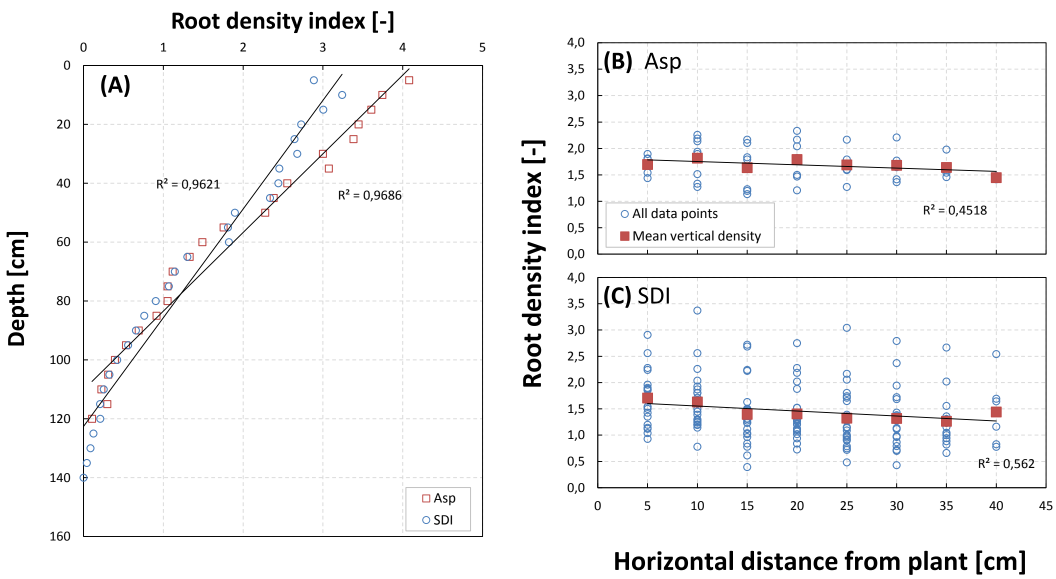

Figure 3: The mean horizontal root density distribution (A) for both Asp and SDI maize plots, and the mean vertical root density of Asp (B) and SDI (C).

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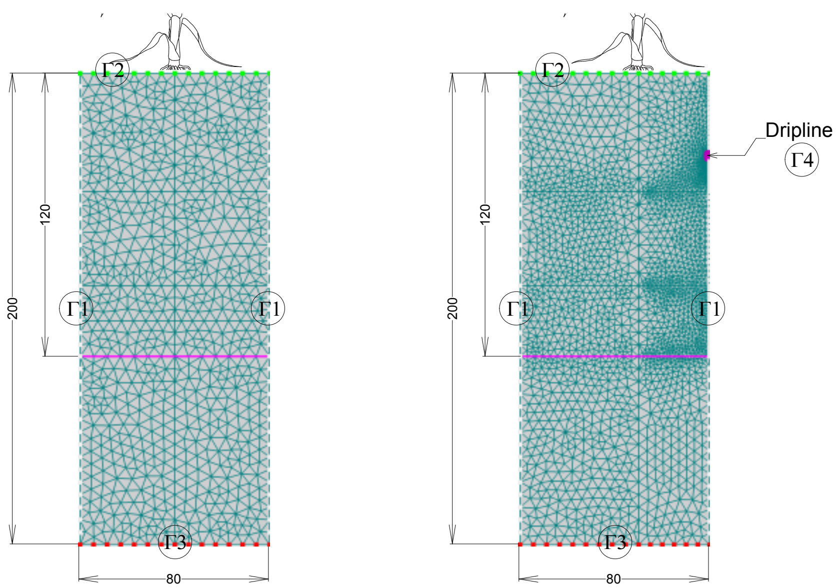

Figure 4: The geometry and boundary conditions (BC's) imposed to the soil domains with dimensions given in cm. Γ1 is a zero horizontal flux BC, Γ2 is an atmospheric BC, Γ3 is a constant water-content BC and Γ4 is a variable flux BC. The horizontal pink line at 120 cm represents the maximum root depth at which drainage was calculated.

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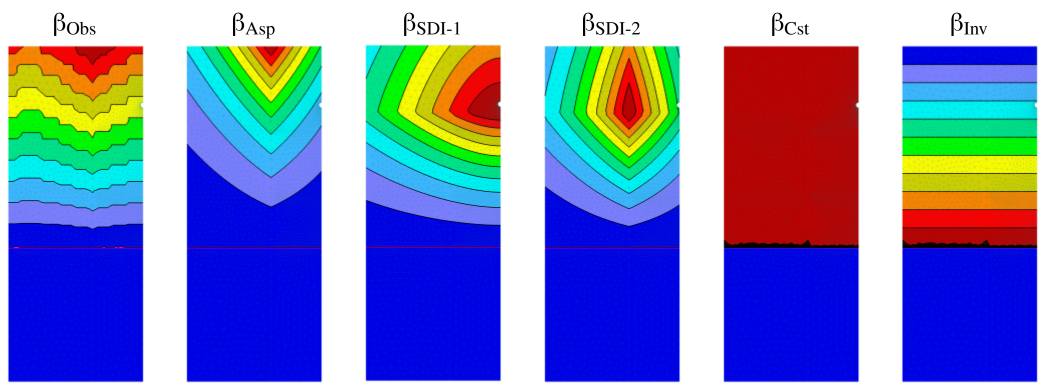

Z_{max} [cm]	120.0	120.0	120.0	120.0	120.0	120.0
Z^* [cm]	0.0	0.0	40.0	40.0	-	-
P_Z [-]	-	2.0	2.0	2.0	-	-
X_{max} [cm]	40.0	120.0	120.0	120.0	40.0	40.0
X^* [cm]	0.0	50.0	80.0	50.0	-	-
P_x [-]	-	4.3	3.0	4.3	-	-

Figure 5: Root density profiles of fully-developed maize irrigated with SDI with driplines located on the right-side boundary at a depth of 40 cm. X^* and Z^* are the horizontal and vertical coordinates at which the root density is maximum. X_{max} and Z_{max} delimit the soil region occupied by roots. P_x and P_z are empirical shape parameters (specific to the function of **?**).

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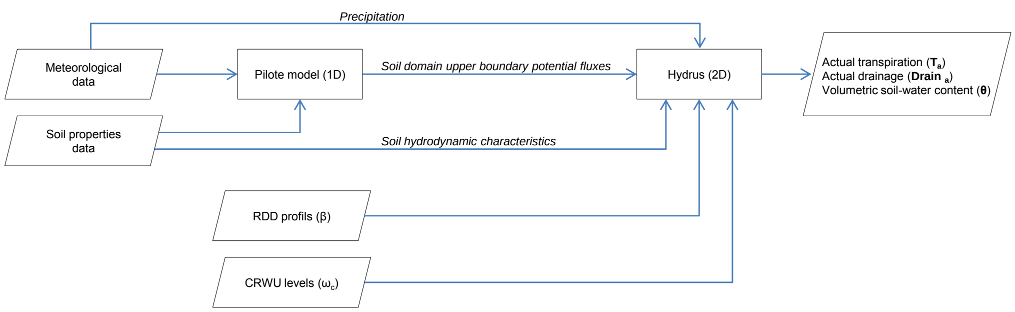

Figure 6: Flowchart of the simulations with Hydrus (2D/3D).

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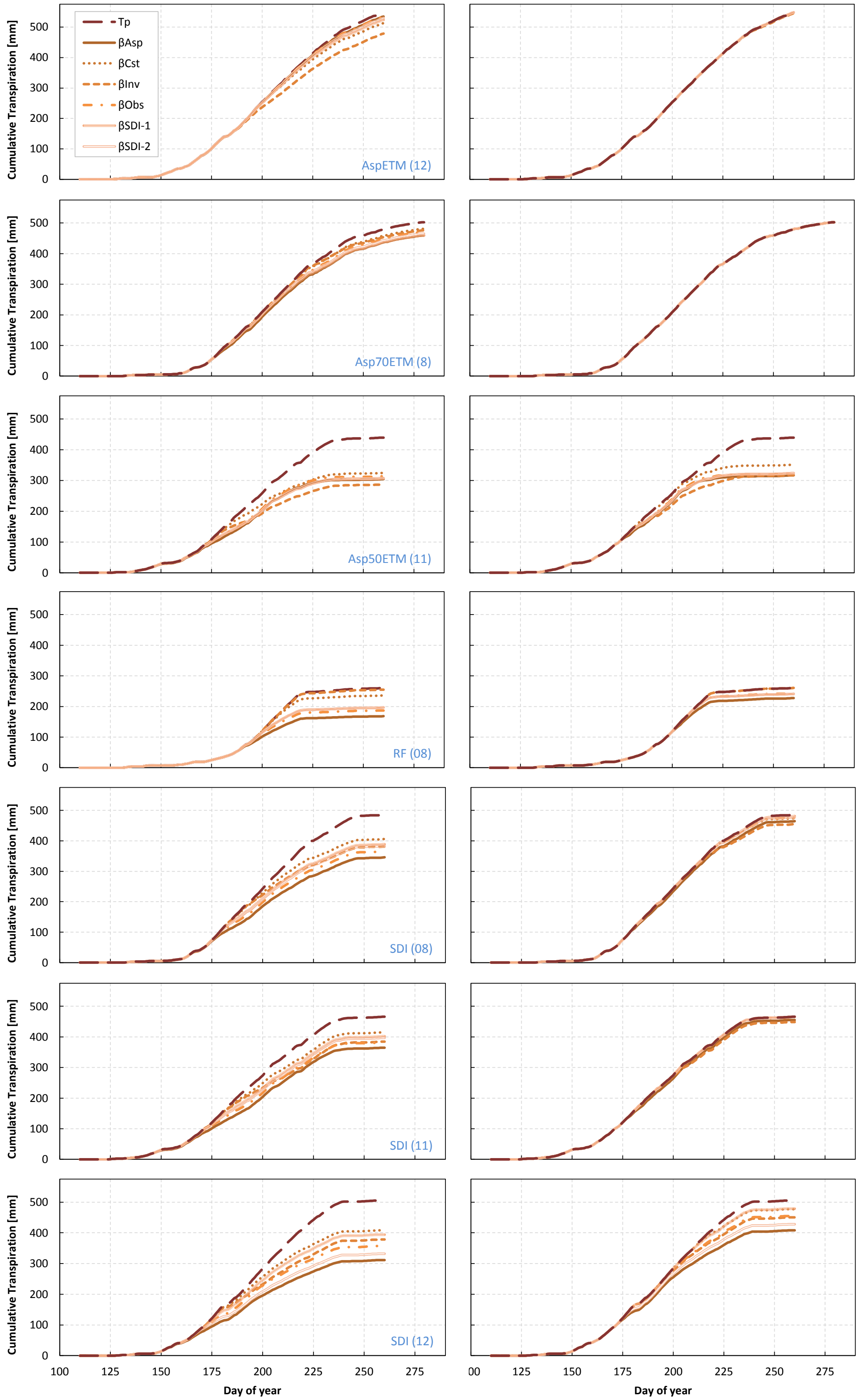

Figure 7: The cumulative transpiration curves $T_{a\,cum}$ simulated with non compensatory (left column) and the maximum compensatory (right column) RWU levels.

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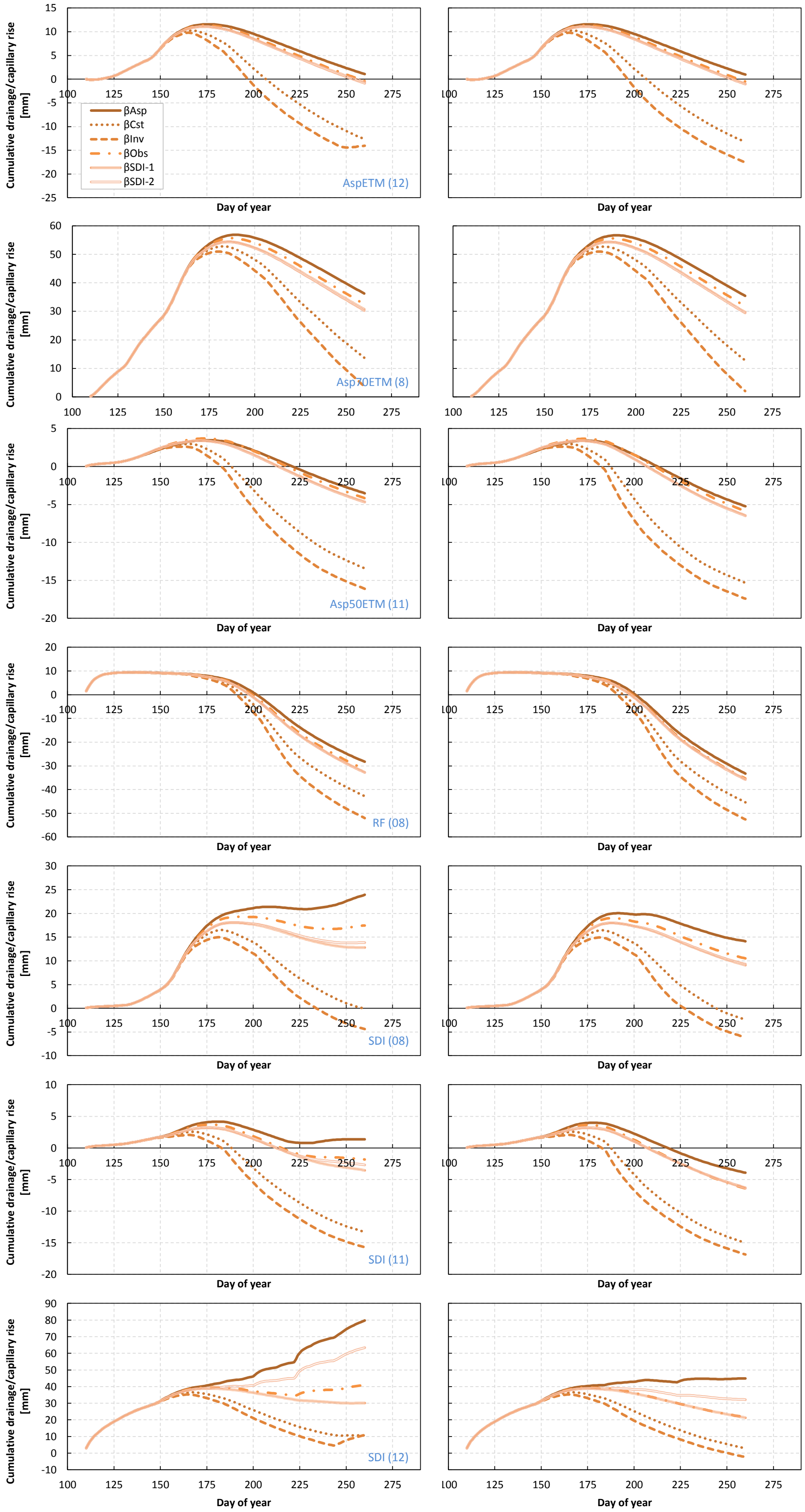

Figure 8: Cumulative drainage/capillary rise outfluxes simulated with non compensatory (left column) and the maximum compensatory (right column) RWU levels. Vertical bars represent rainfall and irrigation events.

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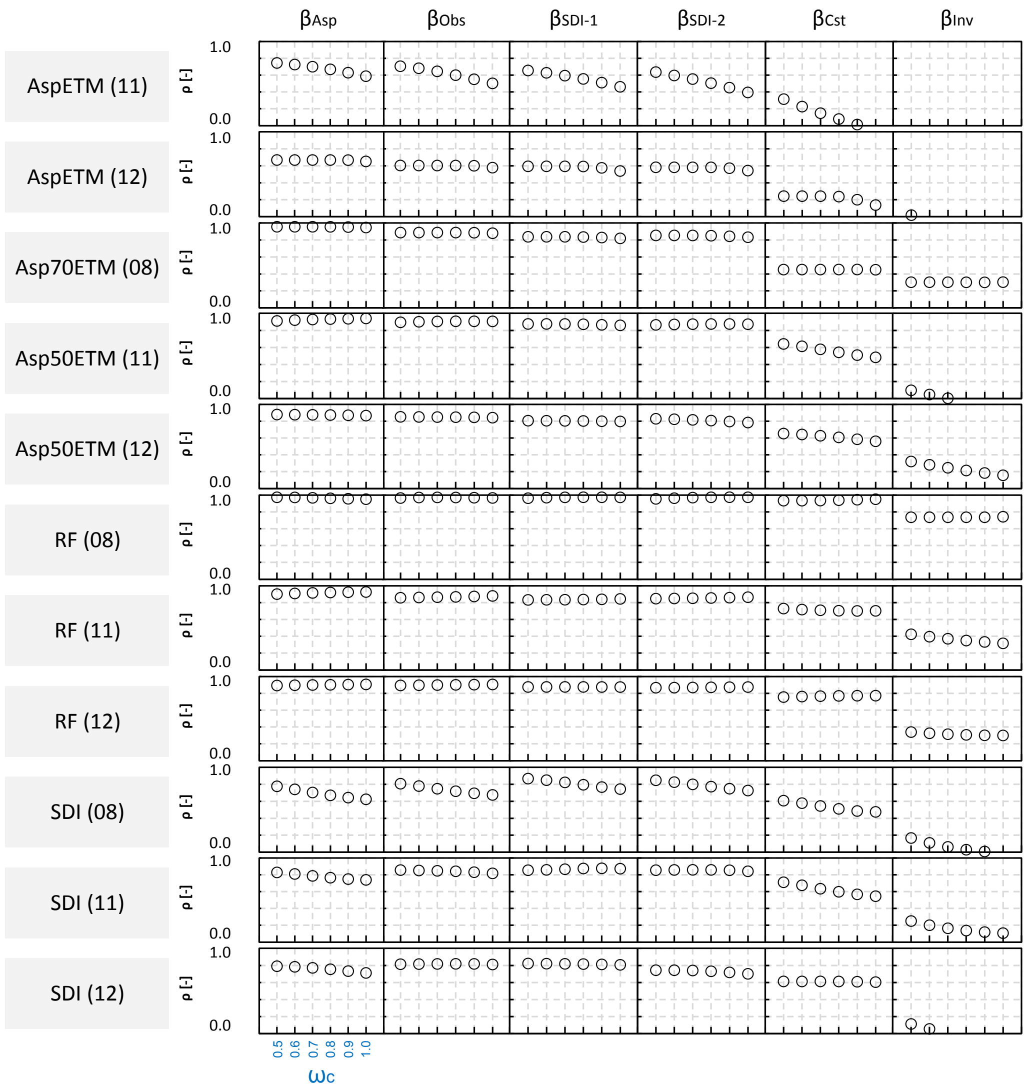

Figure 9: Correlation coefficient of Pearson (ρ) between θ_{obs} and θ_{sim} profiles for all scenarii. Only the positive ρ values are shown.

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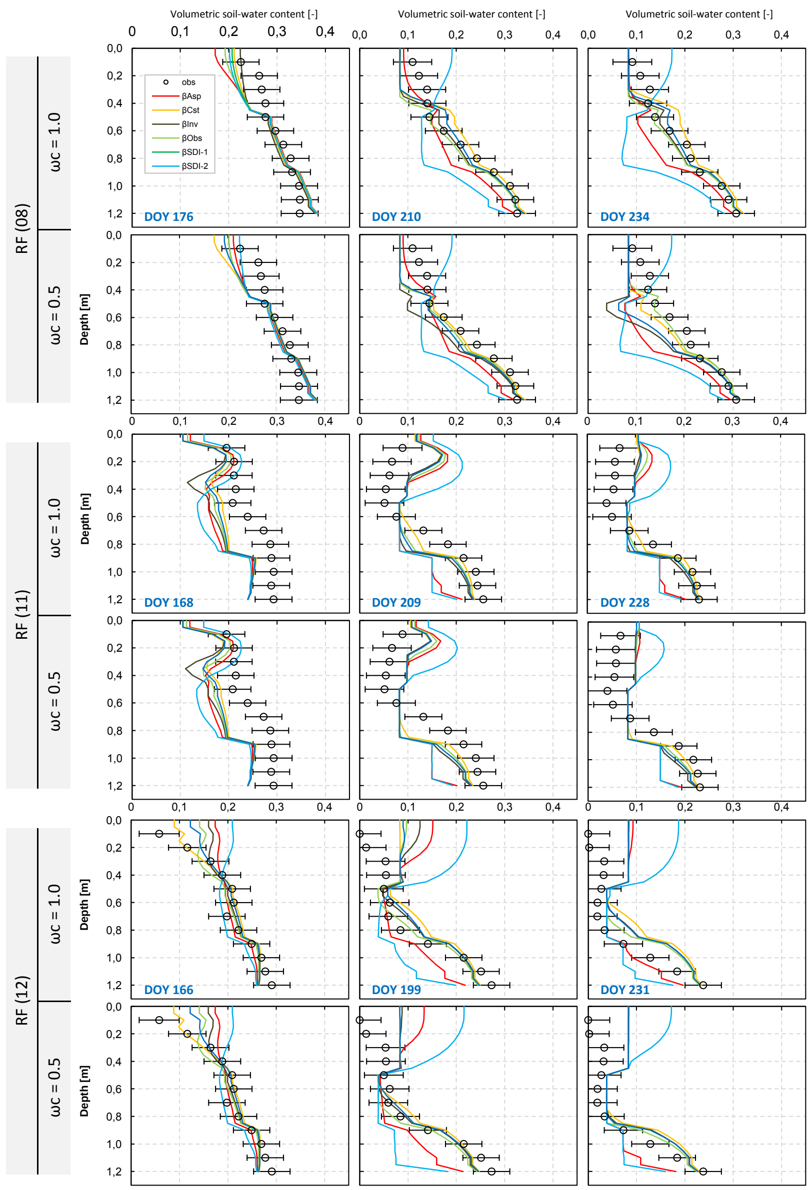

Figure 10: Comparison between θ_{sim} and θ_{obs} for all rainfed treatments, for non and maximum compensatory RWU level. The horizontal bars represent measurement errors corresponding to the neutron probe calibration equation.

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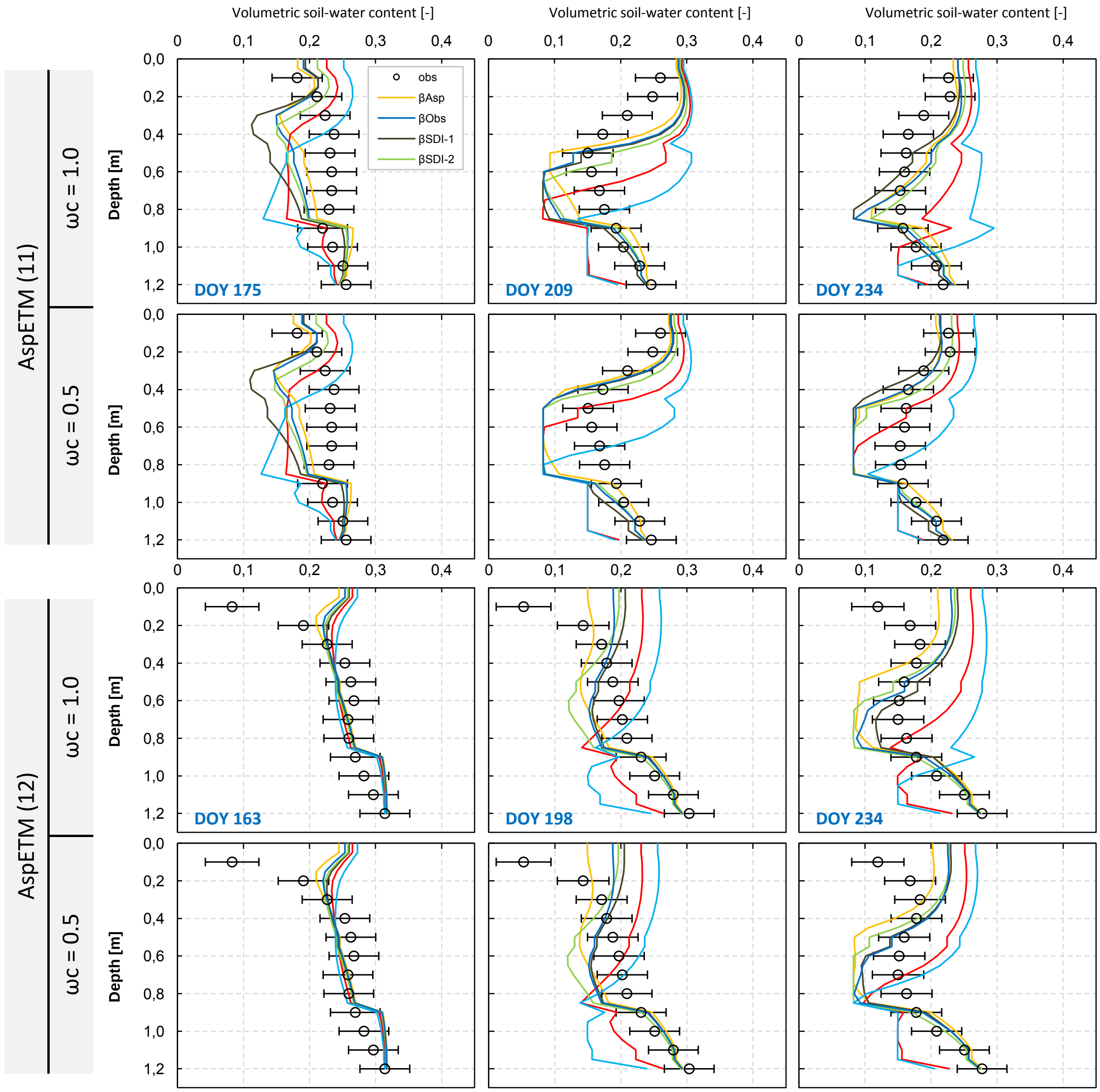

Figure 11: Comparison between θ_{sim} and θ_{obs} for the fully-irrigated sprinkler treatments, for non and maximum compensatory RWU level. The horizontal bars represent measurement errors corresponding to the neutron probe calibration equation.

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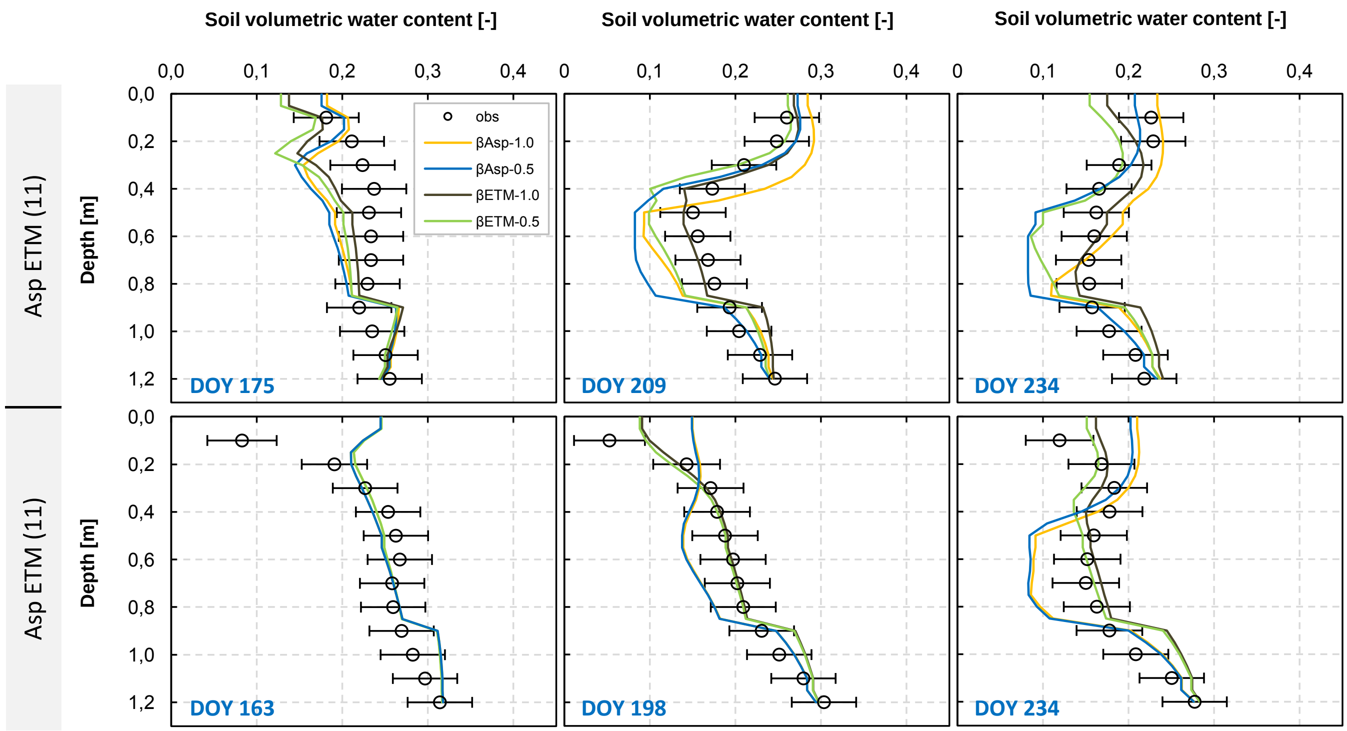

Figure 12: Comparison between θ_{sim} and θ_{obs} for the fully-irrigated treatments. The simulations were conducted using β_{Asp} and β_{ETM} profiles, for non and maximum compensatory RWU level. The horizontal bars represent measurement errors corresponding to the neutron probe calibration equation.

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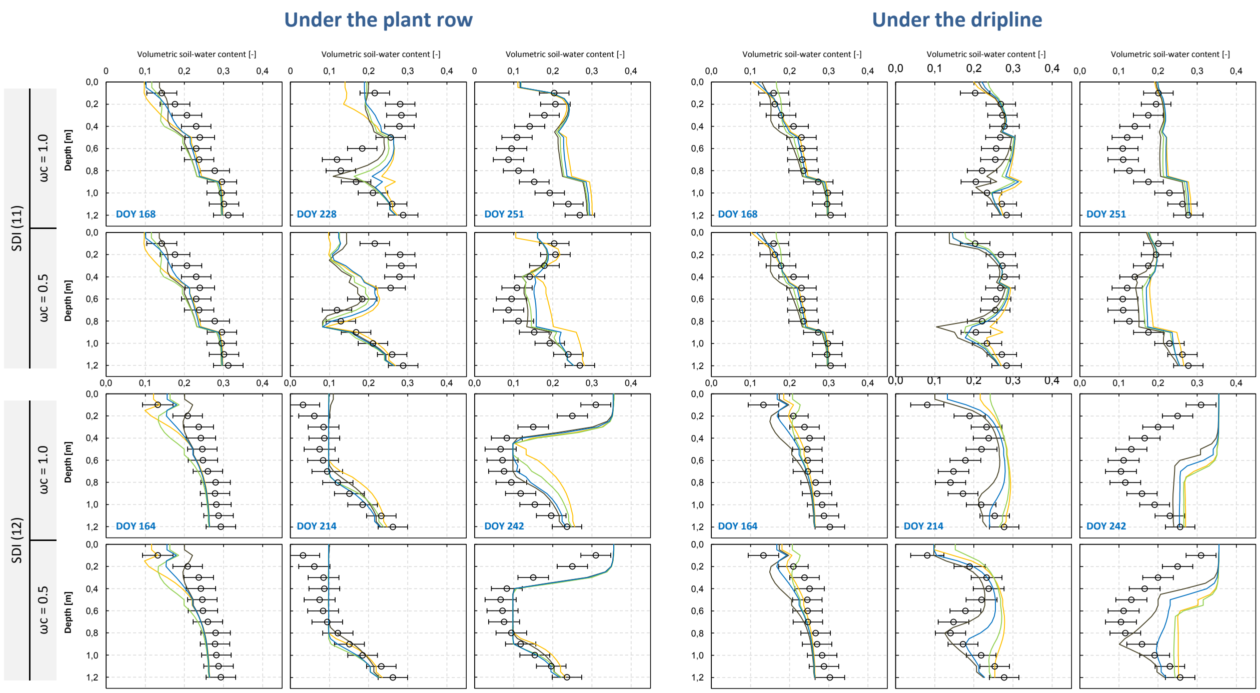

Figure 13: Comparison between θ_{sim} and θ_{obs} under plant row and in the vertical plane of the dripline for SDI (11) and SDI (12), for non and maximum compensatory RWU levels. The horizontal bars represent measurement errors corresponding to the neutron probe calibration equation.

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Soil layer [cm]	clay (%)	silt (%)	sand (%)	θ_r[-]	θ_s[-]	α [cm^{-1}]	n [-]	Ks [cm day^{-1}]	l [-]
0 - 55	18	42	40	0.00	0.36	0.0436	1.227	40.56	0.5
55 - 90	22	47	31	0.05	0.38	0.013	1.45	12.00	0.5
> 90	25	52	18	0.09	0.41	0.019	1.31	6.19	0.5

Table 1: The hydrodynamic parameters of the van Genuchten (1980) model fitted to the soil of Lavalette station. θ_r and θ_s denote respectively the residual and saturated volumetric soil water contents, α and n are empirical shape parameters, Ks is the soil hydraulic conductivity at saturation and l is a pore connectivity parameter.

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	All β profiles				"Realistic" β profiles (β_{Asp}, β_{Obs}, β_{SDI-1} and β_{SDI-2})			
	Non compensatory ω_c = 1.0		Compensatory uptake ω_c = 0.5		Non compensatory ω_c = 1.0		Compensatory uptake ω_c = 0.5	
	Max-Min [mm]	1-min/max (%)	Max-Min [mm]	1-min/max (%)	Max-Min [mm]	1-min/max (%)	Max-Min [mm]	1-min/max (%)
AspETM (11)	63	14.0	52	10.2	9	2.0	6	1.3
AspETM (12)	56	10.5	3	0.6	11	2.1	0	0.1
Asp70ETM (08)	22	4.5	0	0.0	11	2.4	0	0.0
Asp50ETM (11)	38	11.6	34	9.6	9	2.9	7	2.1
Asp50ETM (12)	36	10.7	28	8.0	10	3.3	5	1.5
RF (08)	87	34.1	33	12.6	28	14.5	15	6.4
RF (11)	28	15.4	27	14.0	6	3.7	8	4.4
RF (12)	59	23.3	35	13.0	16	7.5	9	3.8
SDI (08)	60	14.8	26	5.4	43	11.1	16	3.4
SDI (11)	50	12.0	17	3.6	37	9.2	10	2.2
SDI (12)	97	23.7	71	14.8	83	21.1	71	14.8

Table 2: The differences between the maximum and the minimum simulated cumulative transpiration $T_{a\,cum}$ for each treatment, using all β profiles (columns 2 to 5) and only those of the "realistic" group (columns 6 to 9).

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	All β profiles		"Realistic" β profiles (β_{Asp}, β_{Obs}, $\beta_{SDI\text{-}1}$ and $\beta_{SDI\text{-}2}$)	
	Non compensatory $\omega_c = 1.0$	Compensatory uptake $\omega_c = 0.5$	Non compensatory $\omega_c = 1.0$	Compensatory uptake $\omega_c = 0.5$
AspETM (11)	7	6	1	1
AspETM (12)	15	19	2	2
Asp70ETM (08)	36	37	6	6
Asp50ETM (11)	13	12	1	1
Asp50ETM (12)	16	16	2	2
RF (08)	24	19	5	3
RF (11)	5	5	1	1
RF (12)	15	15	2	2
SDI (08)	28	20	11	5
SDI (11)	17	13	5	3
SDI (12)	69	47	50	24

Table 3: The differences between the maximum and the minimum simulated cumulative drainage $Drain_{cum}$ outfluxes for each treatments, using all β profiles (columns 2 and 3) and only those of the "realistic" group (columns 4 and 5).

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(a) non compensatory RWU	β_{Asp}		β_{Obs}		β_{SDI-1}		β_{SDI-2}		β_{Cst}		β_{Inv}	
AspETM (11)	0.064	a	0.074	a b c	0.082	a b c	0.071	a b	0.082	b c	0.085	c
AspETM (12)	0.065	a b	0.062	a b	0.057	a	0.071	a b	0.071	a b	0.083	b
Asp70ETM (08)	0.039	a	0.043	a	0.048	a	0.049	a	0.078	b	0.086	b
Asp50ETM (11)	0.043	a	0.044	a	0.047	a	0.051	a	0.083	b	0.108	c
Asp50ETM (12)	0.055	a	0.060	a b	0.073	b c	0.061	a b	0.088	c d	0.101	d
RF (08)	0.049	a	0.047	a	0.045	a	0.051	a b	0.056	a b	0.082	a b
RF (11)	0.075	a	0.085	a b	0.092	b c	0.085	a b	0.108	c d	0.118	d
RF (12)	0.119	a	0.117	a	0.116	a	0.112	a	0.102	a	0.111	a
SDI (08)	0.061	a	0.054	a	0.053	a	0.054	a	0.062	a	0.081	b
SDI (11)	0.057	a	0.047	a	0.048	a	0.052	a	0.064	a	0.080	b
SDI (12)	0.055	a	0.053	a	0.048	a	0.067	a	0.083	b	0.113	c
(b) compensatory RWU												
AspETM (11)	0.081	a	0.083	a	0.092	a	0.082	a	0.089	a	0.088	a
AspETM (12)	0.067	a b	0.063	a b	0.060	a	0.072	a b	0.071	a b	0.084	b
Asp70ETM (08)	0.039	a	0.042	a	0.046	a	0.051	a	0.079	b	0.088	b
Asp50ETM (11)	0.054	a	0.055	a	0.056	a	0.063	a	0.084	a	0.105	b
Asp50ETM (12)	0.055	a	0.063	a b	0.075	b c	0.060	a b	0.089	c d	0.101	d
RF (08)	0.056	a	0.061	a	0.061	a b c	0.071	a	0.066	a	0.084	a
RF (11)	0.087	a	0.095	a b	0.100	a	0.094	a b	0.112	a b c	0.118	c
RF (12)	0.113	a	0.098	a	0.111	a	0.107	a	0.098	a	0.105	a
SDI (08)	0.063	a	0.056	a	0.064	a b	0.065	a b	0.070	a b	0.085	b
SDI (11)	0.072	a	0.070	a	0.079	a	0.081	a	0.077	a	0.082	a
SDI (12)	0.064	a	0.062	a b	0.050	a	0.074	b c	0.086	c d	0.106	d

Table 4: Root-mean-squared errors (RMSE) [-] between θ_{sim} and θ_{obs} profiles for non compensatory (a) and compensatory uptake (b) simulations. RMSE values followed by the same letters indicate no statistically significant differences (α = 0.5).