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# True water constraint under a rainfall interception experiment in a Mediterranean shrubland (Northern Tunisia): confronting discrete measurements with a plant-soil water budget model

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2

3 True water constraint under a rainfall interception experiment in a Mediterranean  
4 shrubland (Northern Tunisia): confronting discrete measurements with a plant-soil  
5 water budget model.

6

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16

1 Abstract

2 Increased drought length and intensity is expected in the Mediterranean basin under  
3 anthropogenic increase in atmospheric CO<sub>2</sub>, leading to extreme events not yet  
4 encountered in the present climate variability. Understanding ecosystems responses  
5 and capturing peculiar ecophysiological processes related to these events have been  
6 investigated in the field by rainfall manipulation experiments. Quantifying the actual  
7 drought faced by the ecosystem under control and dry plots, or among experiments  
8 remain a key challenge for explaining functional impacts on plant growth. Full profile  
9 soil water content can be tricky to assess in rocky soils, and time consuming plant  
10 water potential measurements remain a discrete information unable to capture short  
11 rainfall pulses. We propose here to fully investigate the water budget of a total rainfall  
12 interception manipulation on a Mediterranean shrubland, coupled with a plant-soil  
13 water balance model. We could accurately simulate the seasonal course of plant water  
14 status, including small rainfall pulses. We then derived yearly estimates of Water  
15 Stress Integral for each water treatment leading to an estimate of 66% to 86% increase  
16 of drought intensity for the dry treatment compared to the control. Comparing actual  
17 and expected plant water budget from simulations in the dry plots allowed to identify  
18 and quantify the impact of methodological issues related to rainfall interception  
19 experiments as side effects for intrusive rain drops and subsurface lateral water flow.

20

21 Keywords : Drought; climate change; extreme event; rainfall interception experiment;  
22 Mediterranean climate; shrubland; water model

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Introduction

Water limited ecosystems experience recurrent dry spells, leading to prolonged soil water deficit. The timing, duration and intensity of these drought periods are critical variables for ecosystem functioning and can be highly variable in space and time (Ruffault et al. 2013). They control the seasonal pattern of plant water status, stomatal conductance for leaf gas exchanges, and in turn leaf phenology, carbon assimilation, plant growth, seed production, and fuel combustibility leading to increasing fire risk (REF). Plant response to this rainfall deficit can however be very heterogeneous, according to soil available water content and species ecophysiological traits for water use (Ackerly 2004, Galmes et al. 2007, Joffre et al. 1999, Quero et al. 2011, Tardieu and Simmoneau 1998, West et al. 2012), including root profile, leaf area index and its phenology or water use strategies. In turn, widely used meteorological drought indices (Dai 2010, Keyantash and Dracup 2012), might be misleading in quantifying actual drought experienced by plants.

In the global context of climate change, and particularly increasing drought predicted globally, more prolonged drought periods are expected, with a higher frequency of the presently observed extreme events, and/or the emergence of more extreme events not yet encountered. To capture the effects of these extreme events on ecosystem functioning and sustainability, rainfall manipulation experiments have been recently developed to simulate these prolonged dry spells on site ( see for review and futur challenges Beier et al. 2012, Jentz et al. 2007, Wu et al. 2011, Vicca et al. 2012). Methods include either partial rainfall interception by permanent gutter removing a constant portion of precipitation for each single rainfall event, or moving shelters intercepting all precipitations during a prolonged period. These experiments can be coupled with watering systems as control plots of well watered conditions. Comparing the results of these experiments recently raised the problem of quantifying the drought

1 intensity actually applied to the studied ecosystems (Vicca et al. 2012). If the rainfall  
2 interception methods are somehow standard between experiments, registered  
3 variables can be heterogeneous according to technical issues. Daily or hourly  
4 meteorological variables are common available datasets registered through  
5 experiments for comparison, but drought is more precisely approached through soil  
6 water content from automated probes or plant water status through fuel moisture  
7 content or species predawn water potentials. The before-mentioned technical issues  
8 include the insertion of soil water probes in the deepest soil layers when soil is rocky,  
9 or the temporal frequency of time-consuming predawn water potential measurements  
10 in mixed ecosystems with heterogeneous water use strategies among species. These  
11 issues can lead to an incomplete understanding of the ecosystem water budget.  
12 Between-site intercomparisons, or even quantification of the actual drought over the  
13 whole dry season between control and dry plots can be difficult or misleading when  
14 based only on the rainfall amount or sparse information on plant water status.  
15 Particularly rainfall pulses have been shown to be significant contributors of plant  
16 functioning in water-limited ecosystems (Sala and Lauenroth 1982), and can be missed  
17 when the time elapsed between two field measurements exceeds the effect of these  
18 rain pulses.

19 Mediterranean ecosystems have to cope with summer drought and climate scenarios  
20 predict an increase of summer rainfall deficit leading to more prolonged drought events  
21 (Giorgi and Lionello 2008). We investigated the effects of these prolonged drought on a  
22 mixed Mediterranean shrubland equipped with a moving shelter to simulate a seven  
23 month total dry spell in Northern Tunisia (North Africa), at the transition zone with semi-  
24 arid climate the most susceptible to be affected by climate change. We completed a  
25 refined campaign of measurements across the dry season to capture both the soil and  
26 plant water status with a special focus on rainfall pulses, deep soil water  
27 measurements, and inter-individual analysis. Our objectives were i) to investigate  
28 precisely the soil water budget across the whole soil profile to identify potential

1 methodological issues related to rainfall interception experiments as deep soil water  
2 diffusion or intrusive rain drops inside the experimental plot from lateral wind or during  
3 the time elapsed to unroll the shelter, ii) identify the daily processes of plant response  
4 to soil water content and rain pulses in order to iii) calibrate a plant-soil water budget  
5 able to simulate the daily time course of plant water potentials across the summer  
6 season when measurements are lacking. We used this model to quantify actual water  
7 stress integral across the season for comparing treatments, and to further discuss plant  
8 water budget during these dry events, and raise potential methodological issues to be  
9 considered in rainfall interception experiments.

10

## 11 1. **Material and Methods**

### 12 1.1 Study site

13 The study was conducted in the Kroumirie territory of Northern Tunisia (North  
14 Africa) near the village of Souk El Jema (Fernana, administrative governorate of  
15 Jendouba; 36.605°N, 8.566°E)( Figure 1). The study area is located on a NW-  
16 facing 20% slope, at an altitude of 529m. The region is characterized by a  
17 Mediterranean climate, with long, dry, and warm summers. Mean annual  
18 temperature is 14.6°C, varying between 10°C in January and 28°C in August. Mean  
19 annual rainfall is 750 mm (5% in summer, 31% in autumn, 29% in spring, and 35%  
20 in winter), with high inter-annual variability but usually with two or three months of  
21 summer drought (source Institut National de la Météorologie, Tunisia, and Direction  
22 Générale des Ressources en Eau, Tunisia). The study area is covered by a  
23 Mediterranean shrubland composed of *Cistus monspeliensis* L., *Erica arborea* L.,  
24 *Phillyrea latifolia* L., *Pistacia lentiscus*, *Callychtoma vilosa*, and *Arbutus unedo*. Soil  
25 texture is sandy clay (65%, 23%, and 12% sand, clay and loam, respectively), with  
26 a low proportion of rock (<5%), 2.5% organic matter, and pH=6. The stand (100  
27 m×70 m) was initially fenced to prevent damage from wild and domestic large  
28 ungulate, and twenty 6 m x 6 m plots were selected. The plots were assigned to

1 five treatments (four plots per treatment), following a randomized, complete block  
2 design, with four blocks arranged parallel to the slope. Plots were subjected to  
3 rainfall manipulations as described below.

#### 4 5 1.2 Rainfall interception protocol

6  
7 A 6 m×6 m steel frame (0.1 m width) was installed in all rainfall manipulation plots 2  
8 m above ground. Four steel posts (2.0 m×0.1 m×0.1 m) supported the frame, each  
9 inserted 0.5 m into the soil. 8 cables were used to maintain the structure. A 6 m×6  
10 m single white PVC sheet (2 mm thick) was installed on top of each base structure.  
11 The PVC shelters unfold and fold by sliding through cables crossing the frame,  
12 manually driven by the 3 permanent security staff ensuring site safety. This manual  
13 system was preferred to the automated one (Misson et al. [2011](#), Parra et al. 2012)  
14 as the site was 3 hours drive from Tunis so it was not possible to quickly repair any  
15 system's failure, and the site had to be secured by permanent staff. A time lag of  
16 20 minutes was needed to unroll all the shelters, usually before rainfall started as  
17 the staff was warned of weather forecasts, and no failure happened during the  
18 experiment. Surface run-off water flowing towards the plot was diverted by digging  
19 a 50cm trench on the upper and side part of the plots. The studied individual plants  
20 were only considered in the central 5 m×5 m area within the 6 m×6 m area covered  
21 by the shelters to try and prevent side effects. Water for irrigation was pumped  
22 through a pipeline system by a hydraulic pressure bomb (600 l.min<sup>-1</sup>, pressure 3  
23 bars) from a container (5,000 L of total storage) located on the upper part of the  
24 stand. The container was refilled after each irrigation by a truck delivering water  
25 from the closest water spring. Plot irrigation was performed manually at night with  
26 water pipes equipped with analogic counters and sprinklers. The full experimental  
27 design and micro-meteorological effects have been earlier described and tested in  
28 Parra et al. (2012) for a similar experiment in Spain. We'll explore here only the two

1 most contrasted treatments: i) the Severe Dry (SD) treatment was a total rainfall  
2 exclusion from May to October in 2011 (6months) and April to October in 2012  
3 (7months), and ii) the Environmental Control (EC) was the actual rainfall pattern  
4 with summer watering when monthly rainfall was below the historical records. Each  
5 treatment was composed in 2011 of 8 replicates for EC, 4 replicates of SD, and 3  
6 replicates for EC and SD in 2012 (due to some plots burned at the end of 2011 for  
7 post fire regeneration assessment, results not shown here). The simulated rainfall  
8 patterns of a lengthened summer drought and precipitation concentrated in winter  
9 were consistent with projections for the Mediterranean region (Christensen et al.  
10 2007).

### 11 12 1.3 Field measurements

13 We installed a fully automated meteorological station on the site with data  
14 acquisition starting April 9<sup>th</sup> 2011. The station registered on a 5-minute time step  
15 (then averaged on a 30min time step) air temperature (°C, sensor Campbell  
16 HMP155A), air humidity (%), VPD (vapor pressure deficit), global solar radiation  
17 (W.m<sup>-2</sup>, sensor Campbell SP1110), PAR (Photosynthetic Active Radiation,  
18 mmol.m<sup>-1</sup>.s<sup>-1</sup>, sensor Campbell SKP215), wind speed (m.s<sup>-1</sup>, sensor Campbell  
19 A100R) and precipitation (mm, sensor ARG100). Data were stored in a data logger  
20 and downloaded for data checking on a monthly basis. Energy is supplied by a  
21 solar panel Photowatt 40Wc. Daily time courses of temperatures (minimum,  
22 maximum and mean), precipitation and solar radiation for the 2011-2012 period are  
23 presented in figure 2.

24 Volumetric soil water content (%) was registered for three soil depths in each plot  
25 using automated probes buried in the center of each plot. A Decagon probe (5HS,  
26 Decagon Devices, United States) installed horizontally at 3cm depth registered the  
27 soil water content for the layer 1-5cm and a Decagon probe (10HS Decagon  
28 Devices, United States) also installed horizontally registered soil water content for



1 the layer 5-15cm. The deep soil water content was registered with a Campbell  
2 CS616 (Campbell Scientific, United States) probe (15-45cm) installed vertically.  
3 Data were continuously recorded on a 5-minute time step, and averaged at 30  
4 minutes intervals.

5 Experimental measurements consisted of leaf predawn water potentials with a  
6 pressure chamber (PMS 1000, PMS Instruments, Corvallis, OR, USA) monitored  
7 before sunrise, with a scheduled interval of one month. Additional measurements  
8 were performed before and after some rainfall/irrigation events during the summer  
9 season to capture rain pulse effects on plant water potentials. Among the panel of  
10 species present on the site, we selected two anisohydric species (sensu Tardieu  
11 and Simmoneau 1998) for which plant water potentials were the lowest during the  
12 dry period and have been assumed to be the closest to soil water potential : *Erica*  
13 *arborea* and *Arbutus unedo*. For each species one individual per plot was selected  
14 with the most central position in the plot, even if the heterogenous composition of  
15 the plots induced individuals to be actually located at the border of the 5mX5m  
16 inner plot.

17

#### 18 1.4 Soil/plant water budget model

19 We used a plant-soil water budget model to simulate daily soil water content,  
20 evaporation and plant transpiration fluxes, and the subsequent plant water  
21 potential. Variations in soil water content (SWC) were simulated using the water  
22 module from the SIERRA process-based vegetation model (Mouillot et al. 2001,  
23 Ruffault et al. 2013), based on the water balance between precipitations and water  
24 outputs.

$$25 \Delta\text{SWC} = P - I_n - D - E - T$$

26 Where the P is daily precipitation (mm),  $I_n$  is the amount of precipitation intercepted  
27 by the canopy (mm), E is bare soil evaporation (mm) and T is transpiration (mm). D  
28 is the resulting deep water drainage. Soil is represented by a 4 layer bucket model

1 (depths 0-5cm, 5-15cm, 15-45cm, 45-100cm). Reference evapotranspiration  $ET_0$   
2 was computed using the Penman-Monteith equation (R cran Package Sirad,  
3 function  $ET_0$ , from Allen et al. 1998). In our two-step approach (Shuttleworth (2007)  
4 for a review of water budget models), reference evapotranspiration  $ET_0$  is controlled  
5 by a canopy resistance and a water stress scalar to get the actual transpiration  $T$ .  
6 This simplified version of the full Penman-Monteith (Penman 1948, Monteith 1965)  
7 approach has been used for forested ecosystems in the same area (Chakroun et al.  
8 2014). Stomatal conductance is simulated using soil water potential, related to soil  
9 water content by the power function model of the retention curve (Van Genuchten  
10 1980). The power function was fitted to the soil water content/plant water  
11 relationship from field measurements.

12 Species functional parameters were Leaf Area Index, rooting depth, minimum water  
13 potential for extraction ( $\Psi_{lim}$ ), and were kept constant throughout the simulation  
14 with respectively values of 2.0 (+/- 0.2), 1.0m, and -7MPa. From this initial model,  
15 we added a diffusion soil water flux from upper layers to the subsequent deeper  
16 ones when relative water content of the upper layer was greater than the lower ones  
17 according to the Darcy's law for vertical unsaturated flow (Muller 1999 and used in  
18 Belk et al. 2007). We also computed water potentials for the whole plant as a  
19 combination of simulated soil water potentials where the whole plant water potential  
20 was 30% of the minimum water potential for soil layers 1 and 2, and 70% of the  
21 minimum water potential for soil layers 3 and 4.

22

### 23 1.5 Numerical experiment

24 We first calibrated model's parameters from field measurements for an accurate  
25 simulation of both soil water content and plant water potentials under current  
26 climate in control plots for the year 2012. The model was then run under rainfall  
27 interception climate scenario with the previously calibrated model to estimate the  
28 expected soil plant water budget in the dry plot (SD-H1). Discrepancies between

1 simulated and actual soil/plant water budget were then investigated according to  
2 two hypothesis: i) SD-H2: 20% of the registered rainfall was able to reach the soil  
3 under the shelter under windy conditions and horizontal rain direction, and ii) SD-  
4 H3: SD-H2 with, in addition some deep soil water which could diffuse into the SD  
5 plot from wetter soil conditions outside of the plot (the soil water budget of the  
6 deeper layer was issued from the EC water budget, and not the SD).

7 The Water Stress Integral (WSI) was finally calculated yearly as the integral of  
8 simulated daily predawn leaf water potentials along the year (Myers 1988,  
9 Wullschleger and Hanson 2006). It was used as the index quantifying actually  
10 drought occurring on each experimental plot.

## 11 12 2. Results

### 13 14 2.1 Seasonal course of soil water content

15  
16 Field measurements of soil water content for the three soil layers (0-5cm, 5-15cm,  
17 15-45cm) for the years 2011 and 2012 are presented in figure 3. The SD treatment  
18 did not receive any rainfall during the whole period while the EC treatment received  
19 190 mm in 2011 and 353 mm in 2012 according to the rainfall distribution  
20 presented in figure 2. We'll note here that 2011 is more characterized by heavy  
21 spring rainfalls (around Day Of the Year DOY=150) while 2012 is more  
22 characterized by a drier spring and a wetter fall period (heavy rainfall events around  
23 DOY 240 and 260). No major difference in temperature nor solar radiation between  
24 the two periods was observed (figure 2). The soil water measurements illustrate  
25 that the three layers were at field capacity at the beginning of the experiment  
26 (15mm, 30mm and 90mm for the three layers respectively). We then observe an  
27 earlier drying of the two upper layers for both years. For the third layer, the earlier  
28 drying of 2011 was not observed in 2012 as no major rainfall event happened after

1 day 120 compared to 2011. After DOY 180, all the plots reached their minimum  
2 water content, whatever the treatment. From this date onwards, the SD treatment  
3 kept constant dry soil water content until DOY 280. The shelters were still installed  
4 until DOY 320, but the heavy rainfalls during consecutive days around DOY 280  
5 lead to partial intrusive water in the SD plots for the three layers and both years  
6 2011 and 2012. The soil water content was still much lower than the EC plots. For  
7 these EC plots, soil water content along the season was marked by peaks of high  
8 moisture when significant rainfalls occurred (> 10mm). These peaks lasted for about  
9 10 to 15 days only. In turn, the two heavy rainfall events at DOY 240 and 260 in  
10 2012, lead to similar soil water content at DOY 280 for both treatments. From DOY  
11 280 until the end of the experiment, soil water content was at field capacity for the  
12 EC plot. We can conclude from these results, that, along a 45cm soil profile, both  
13 treatments reached the same soil water content at their driest. However, the SD  
14 plots were marked by a slight earlier drying in spring, a significant later rewetting in  
15 fall, and the absence of high soil moisture pulses during the summer period.

## 16 17 2.2 Plant water status

18 Figure 4 represents the seasonal measurements of predawn leaf water potentials  
19 (LWP) for *Erica arborea* and *Arbutus unedo* in the SD and EC plots for 2011 and  
20 2012. Measurements were scheduled on a monthly basis. To ensure for relevant  
21 information, more intense field campaigns were performed before and after some  
22 few rainfall/irrigation events. For both treatments, LWP was close to -0.5Mpa at the  
23 beginning of the experiment ensuring a similar initial water status. LWP slowly  
24 decreased in spring to reach -3Mpa at DOY 200 with no significant differences  
25 between the treatments. The lowest values of -6.8Mpa were obtained at the end of  
26 the summer in 2011 and 2012 and for both treatments with no significant  
27 differences.

1 Differences between treatments were observed on one hand after DOY 250 for  
2 both years when LWP was measured at -4MPa in 2011 and -0.5MPa in 2012 in the  
3 EC plots where rainfall occurred, but significantly lower in the SD plots (-6MPa and -  
4 5MPa in 2011 and 2012 respectively). We noticed however high standard  
5 deviations (sd) in the measurements in the SD plots after DOY 250 in 2012 (sd= $\pm$ -  
6 3MPa compared to sd= $\pm$ - 0.8MPa before DOY 250), particularly just after rainfall  
7 events of DOY 260 and 280 in the site, when some individuals were measured at -  
8 6.5MPa and other at -1MPa within the same treatment. This high standard  
9 deviation is not noticed in the EC plot for the same dates. On the other hand,  
10 differences in LWP between the two treatments were noticed during small rainfall  
11 events during the dry season (DOY 210 and 222 in 2012 for example).  
12 Measurements were performed just before and after the rainfall event, so we could  
13 identify that pre-rainfall LWP were at -6.8MPa, and rapidly switched to -4MPa the  
14 day after. Standard deviation after the rainfall was also much higher than before.  
15 When comparing with the soil water content at this date, we can see that this  
16 change of LWP was not associated with significant changes in the total soil water  
17 content (as the rainfall was only 6 mm), but little changes only in the upper soil  
18 layer.

19 As a conclusion from these results, we could show that the rainfall interception  
20 experiment induced neither significant differences in LWP during the spring period,  
21 nor in the minimum LWP reached during the summer season. From discrete LWP  
22 measurements, major differences were only detected at the end of the dry season  
23 and following small rainfall events. We could detect these differences because of  
24 an appropriate field campaign not based on an *a priori* schedule but arranged  
25 according to weather. Post-rainfall measurements at the end of the dry season also  
26 revealed a high standard deviation between individuals, and that could have been  
27 missed with a monthly schedule. Based on these observations where we can  
28 identify the need for more frequent LWP to accurately capture all the variations of

1 LPW along the season, we used a plant-soil water budget model to simulate a  
2 continuous course of LWP to better capture the small events all along the  
3 experiment, including the missed ones in the measurement framework.

### 4 5 2.3 Modelling soil-plant water budget

6 We finally used a process-based soil-plant water budget model to simulate the daily  
7 time course of soil water content and LWP. The model was calibrated for the year  
8 2012 on the control treatment and further used for 2011 and the dry treatment for  
9 validation. Figure 4A represent the daily time course of simulated soil water content  
10 and LWP for the two treatments and for years 2011 and 2012. We observe that  
11 simulations and observations fairly agree with  $R^2=0.86$  and  $0.83$  for the EC plot  
12 respectively in 2011 and 2012 (figure 4B).  $R^2$  is  $0.84$  for the SD plot in 2011 when  
13 field measurements were made before rainfall events, but falls to  $R^2 = 0.48$  when a  
14 more thorough field campaign was performed in 2012 with pre and post rainfall  
15 measurements.

16 From these simulations we can identify that we were able to simulate the slow  
17 spring decrease in LWP, and an accurate representation of summer LWP pulses  
18 induced by small rainfall events. When focusing on this peculiar events (figure 5),  
19 we were able to reproduce both the intensity of changes in LWP before and after  
20 the rainfall, and the subsequent LWP decay during the post-rainfall drying period.  
21 We tested for the model's sensitivity to LAI, a key variable for water budget and  
22 locally varying between the plots (from 1.8 to 2.2). Uncertainties in the resulting  
23 simulated LWP is presented in figure 4, and were mostly observed in the LWP  
24 decreasing phase. We were then confident in the stated hypothesis in the plant  
25 water model for simulating plant water status based on soil water content, for a  
26 further use in quantifying the rainfall interception efficiency.

### 27 28 2.4 Water budget under rainfall interception

1 From our soil-plant water budget model validated on the control treatments, we  
2 performed a simulation run for 2011 and 2012 with no rainfall all along the period  
3 (figure 6). The simulated soil water budget showed a lower than observed soil  
4 water content during the drying phase in spring under scenario SD-H1, with about a  
5 time lag of 30 to 35 days (figure 4). These discrepancies are also observed in the  
6 LWP simulations under the SD-H1 scenario (figure 6). The model then simulated a  
7 maintenance of LWP at -7Mpa all along the dry season from DOY 180 to 320. This  
8 result is partly in accordance with the field measurements where some individuals  
9 actually kept a similar low LWP around -7MPa until late in the season in the dry  
10 treatment and did not exceed this value. However, as we mentioned in the LWP  
11 results description, we observe a high inter-individual variability after DOY 260  
12 when heavy rainfalls occurred on the site. We then tested the hypothesis that some  
13 individuals would be affected under SD H2 and SD H3 hypothesis. Figure 6  
14 represents the plant water budget under these two additional hypothesis and  
15 illustrates how they would actually affect plant water status. With these simulations,  
16 we produced a range of variability in accordance with field measurements, where  
17 LWP can vary from -7Mpa under the SD H1 scenario, and up to -3MPa if water  
18 enters the system under SD H2 scenario.  $R^2$  between observed and simulated  
19 LWP was increased from 0.48 under SD H1 scenario to 0.59 under SD H2 and  
20 SDH3 scenarios. They were accounted for the overall estimate of the experimental  
21 drought intensity through the Water Stress Integral.

## 22

### 23 2.5 Quantifying rainfall interception efficiency through Water Stress Integral

## 24

25 We finally quantified the efficiency of our rainfall interception experiment by  
26 comparing the water stress integral WSI for the EC, and SD experiments covering  
27 experimental bias stated in hypothesis SD H2 and SD H3. WSI for the EC plot was  
28 -425 (+/- 34) MPa and -434 (+/- 30) MPa for 2011 and 2012 respectively (figure 7).

1 This value was -790 (+/- 35) MPa and -1025 (+/-25 MPa) for the expected WSI  
2 under rainfall interception SD H1 hypothesis respectively for 2011 and 2012. We  
3 estimated finally the actual WSI under SD H3 scenario to be -699 (+/- 35MPa) for  
4 2011 and -752 (+/-32Mpa) for 2012. In turn, from an initial hypothesis where a 30%  
5 rainfall interception was performed, the resulting impact on WSI was a +64-73%  
6 increase, lower than the expected 86-136% increase if the rainfall interception was  
7 actually complete. From this final yearly value, the seasonal time course of  
8 cumulated water potentials (figure 7) shows that we reached a 15% increase of  
9 WSI at the end of summer (DOY 250). The main difference in the treatments for the  
10 yearly WSI was mostly due to the fall period difference between treatments when  
11 the deeper soil layer is dry.

12

### 13 3. Discussion

14

#### 15 3.1 Soil water content and plant water potential relationship

16

17 It is widely assumed, for comparative ecological performances or modelling  
18 purposes that plant predawn water potentials reflect the wettest soil potential  
19 accessed by roots. In this hypothesis, plants are able to recover from their diurnal  
20 water depletion by absorbing water from the different soil layers until plant water  
21 potential reaches the water potential in this soil layer. In turn, as long as a soil layer  
22 is enough watered for providing a gradient of potentials between the soil and the  
23 plant, a water flux happens. This assumes a non-steady-state phase between plant  
24 and soil, where the plant water content is represented by a reservoir depleted  
25 during the day and refilled at night when no transpiration occurs but root water  
26 uptake happens (Lhomme et al. 2001). There are however evidences of predawn  
27 disequilibrium (PDD) in water-limited ecosystems as a response to peculiar  
28 ecophysiological processes as night-time transpiration or leaf apoplastic solutes for



1 a resistance to rehydration (Donovan et al. 2003). Beside this observed process  
2 of PDD in some semi-arid conditions, the predawn soil-plant water potential  
3 equilibrium presents exceptions when soil water content is markedly  
4 heterogeneous among different soil layers (Ameglio et al. 1999). This partial root-  
5 zone drying (PRD) is actually a common event in the deficit irrigation practice,  
6 where water from irrigation is only provided in the upper part of the root profile while  
7 deeper roots remain in dry conditions. This practice is widely applied for permanent  
8 crops as olive trees in the Mediterranean basin (Fernandez et al. 2003, Ghrab et al.  
9 2013). The objective is to reactivate gas exchanges at the canopy level and in turn  
10 plant functioning under drought conditions, but with a maximum water saving  
11 strategy as rehydrating part of the soil profile is enough for providing plant water  
12 potentials suitable for stomatal aperture. This peculiar practice is actually close to  
13 our natural and experimental conditions in the studied area, where small  
14 rainfall/watering events during the summer drought rehydrate the upper soil layers  
15 without refilling the deeper layers, or on the contrary when the upper soil layers  
16 start to dry out in late spring while the deeper layer is still well watered. We could  
17 indeed identify that rainfall events of 5 to 15mm could refill the upper soil layer to  
18 field capacity and have significant impact in reducing the plant predawn water  
19 potential. However, we never reached predawn water potentials at the level of  
20 potentials observed during winter when the whole soil profile is at field capacity. In  
21 turn, the hypothesis of the minimum soil water potential to be retained for  
22 approximating the plant water potential was discarded, and adjusted as explained  
23 in the model description. As the plant functioning period in water limited  
24 ecosystems is constrained by stomatal closure and plant water potentials,  
25 understanding the plant response to partial soil water refill appears as a key  
26 process to further investigate in plant ecology.

27

28 3.2 Ecohydrological role of rainfall pulses

1 Our results indicated that small rainfall events during dry periods are able to provide  
2 substantial, even if not complete, recovery of plant water potential closer to -  
3 0.5MPa through the soil surface rewetting. This change in plant water status is  
4 usually associated with an increase in stomatal conductance, transpiration flux and  
5 photosynthesis (Loik et al. 2007). In semi arid ecosystems, implications for carbone  
6 assimilation (Huxman et al. 2004) and plant growth can be significant (Ramirez et  
7 al. 2012). These pulses are however hard to detect in the discrete sampling of plant  
8 predawn water potential, the key variable used for comparing plant water status.  
9 We suggest here to be more carefull on these pulses under Mediterranean climate,  
10 and particularly for shallow rooted species as shrublands, to accurately account for  
11 the actual drought experienced by plants along the summer season. These pulses  
12 could be highly significant for shrublands with a subsequent ecological role already  
13 identified for arid ecosystems (Sala and Lauenroth 1982, Schwinning and  
14 Ehleringer 2001, Schwinning and Sala 2004). For deep-rooted forested species,  
15 extreme drought could be more dependant on changes in winter precipitation  
16 refilling or not the deep soil water content (Yaseef et al. 2009, Limousin et al. 2009).

17 The threshold-delay conceptual model (Ogle and Reynolds 2004, Burgess  
18 2006) identifies four main critical values to assess when analysing plant response  
19 analysis to rainfall pulses: the effective rainfall amount needed for actually  
20 modifying plant water status, the response size describing the change in plant  
21 water status, the response delay for the time needed for the plant respond to this  
22 effective rainfall, and the decay rate for the post-rainfall plant water status decay  
23 after the plant responded. We identified here a critical rainfall of about 6-8 mm for  
24 the plants to respond, with no response delay, a response size of about 3MPa  
25 depending on the rainfall intensity and a decay rate of 0.3MPa.day<sup>-1</sup> corresponding  
26 to the actual evapotranspiration rate in summer. Irrigation experiments with  
27 different rain intensities would allow for a better understanding of specific  
28 responses for climate change impact assessment.

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### 3.3 Ecohydrologically-sound drought quantification

Quantifying drought for climate change studies remain a key challenge to provide valuable information for agriculture and ecosystems (Dai et al. 2001). From global scale studies using generic indices as SPI and SPEI as indicator of major ecosystem functioning (Vicente-Serrano et al 2012), local scale studies point out the weaknesses of these indices for an accurate quantification of drought due to soil and ecophysiological processes (Keyantah and Dracup 2002). Plant-soil water budget models remain the best tools to provide information when climate, soil and plant information are available, and provide continuous information on plant predawn water potential when discrete measurements are time consuming (Zweifel et al. 2005). Water stress integral (WSI) (Myers et al. 1988) is now increasingly used for quantifying drought features in rainfall interception experiments (Wullschleger et al. 2006, Nepstad et al. 2007) or regional assessments (Ruffault et al. 2013, 214). We recommend here this index as a tool for effective comparison between treatments in rainfall interception experiment as an integrated index accounting for rain pulses.

### 3.4 Rainfall interception issues and recommendations

From our analysis we could quantify the actual impact of the rainfall manipulation based on an ecohydrologically-sound index, the Water Stress Integral. This index allowed us to assess the seasonal impact of the experiment and its overall efficiency. This index was also used as an indicator of potential biases of the experiment. We identified:

- i) some difficulties to create spring drought right after the starting of the experiment. In march, ET0 is still low while soil water content is at field capacity. We managed to desiccate the upper soil layers, but it was difficult to dry out the

1 deeper soil layers. We suspect some capillarity effect in this deeper layer with  
2 lateral water flows, particularly at the boundary with the non fragmented rock layer  
3 where drained water from the upslope might follow this surface and keep wet until  
4 soils from the whole watershed is fully drained with a significant time lag after the  
5 last rainfall event. Upward capillarity from this boundary to the deeper layers might  
6 occur as observed in sites where a water table is observed (Nepstad). In turn,  
7 winter water deficit limiting this drainage might actually be more significant on this  
8 period than the spring water deficit itself (Yaseef et al. 2009 ). Fewer fine roots in  
9 this deeper layer, combined with reduced evaporation might also limit water uptake  
10 and keep this layer humid longer than the upper ones. Low differences in plant  
11 water status was also observed in spring for a similar rainfall interception under  
12 Mediterranean climate (Ramirez et al. 2012) but hardly assessed or quantified.

13 – ii) side effects might occur so that individual plants in the center of the plot  
14 experience a more intense drought than the external ones. Despite keeping a safety  
15 band of 1m inside the plot, we hypothesised both some raindrops insertions during  
16 windy conditions are able to rehydrate the upper soil layers, and that the lateral  
17 spread of the rooting system could reach soil water outside the experiment. This  
18 processes has been suggested by Throop et al. (2012) and lateral root profile  
19 analysis in mediterranean ecosystems could support this hypothesis (Canadell and  
20 Zedler 1995). The experimental protocol was designed to keep a safety band of 1m  
21 inside the plot, and to dig trench around the plots, but these might not be sufficient  
22 for a total interception. This was evidenced by the high standard deviation of plant  
23 water potentials after rainfall events inside the plots. Our simulations evidenced  
24 that only a 20% entrance of external rainfall under the roof would significantly  
25 modify the water potential of plants located close to the side of the plot.

26 We'll conclude this analysis that rainfall interception in shrublands are efficient  
27 tools to assess the effects of increasing drought on ecosystem functioning.  
28 However, we warn here that a full understanding of the deep soil layer water

1 budget might mitigate the expected impact due to lateral water movement when  
2 soils a fully humid after the winter season. In turn the rainfall interception is more  
3 efficient in the rewetting season in fall. Also, fine temporal scale measurements of  
4 plant water status in the dry plots after rainfall events would be a valuable  
5 information to quantify any side effect, and anisohydric species could be target  
6 individual to quantify these effects.

#### 7 8 4. Conclusion

9 We performed here a total rainfall interception experiment on a maquis shrubland  
10 under Mediterranean climate, with a thorough understanding of the soil and plant  
11 water budget. We could propose an accurate water budget model able to simulate  
12 both the soil water content, and plant responses in term of predawn leaf water  
13 potential (LWP), a key variable for leaf gaz exchange and the subsequent plant  
14 carbon budget, growth or cavitation and branch die back. Our results could identify  
15 the more significant role of small rainfall events during the dry period when  
16 compared to the low impact of rainfall interception on the spring soil desiccation  
17 rate. Also the minimum threshold of LWP reached and kept constant all along the  
18 season whatever the treatment was not a key indicator in our shallow soil. We  
19 identified also limitations in experimental design with scheduled and regular field  
20 measurement and rainfall interception systems efficiency. Sparse measurements of  
21 LWP can be misleading and more emphasis should be devoted to pre/post rainfall  
22 events. Deep soil water movements and side effects on intrusive rain drops should  
23 be addressed in details for a more precise quantification of the actual experiment  
24 efficiency. The importance of these effects might be heterogeneous according to  
25 soil depth, slope or wind and water budget models could be valuable tools to  
26 investigate these effects. Watering experiments might in turn be more effective and  
27 more easy to control (Wu et al. 2011)

28

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7        install the experiment.

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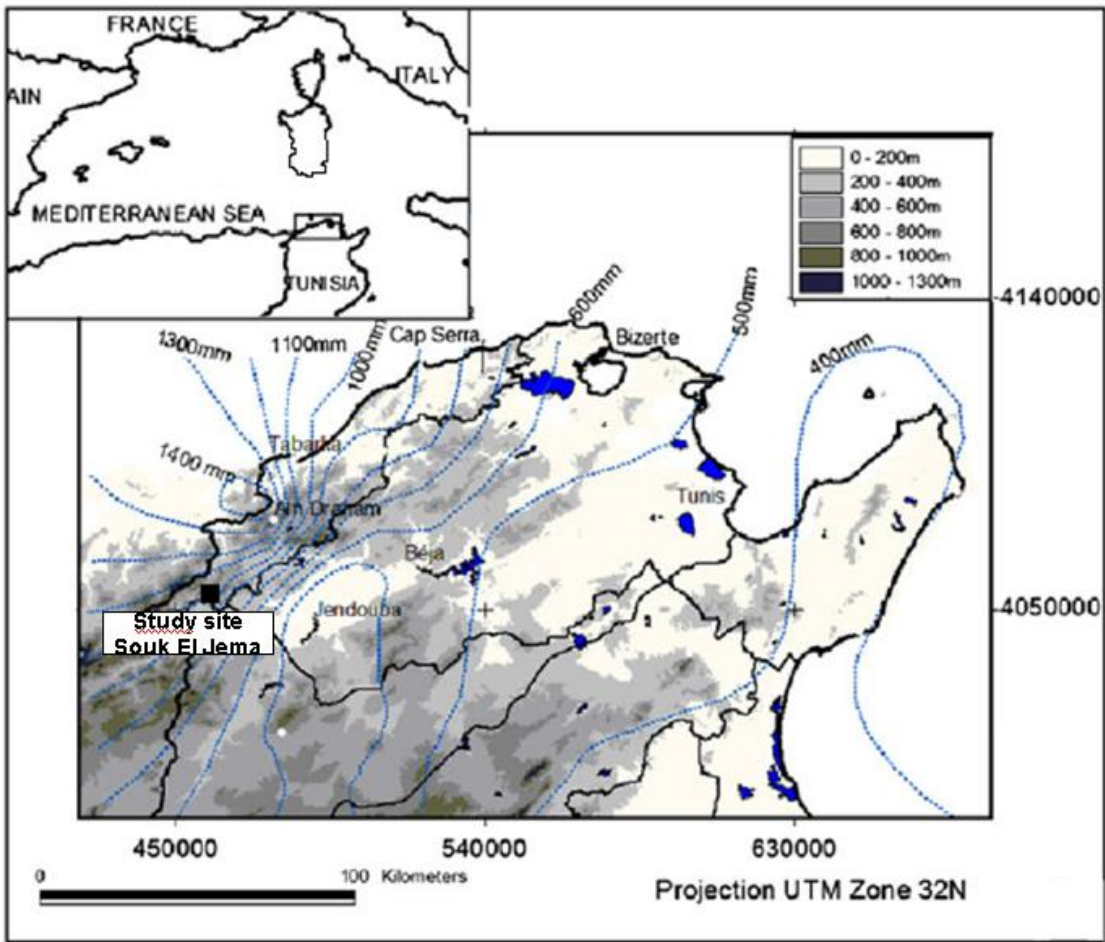


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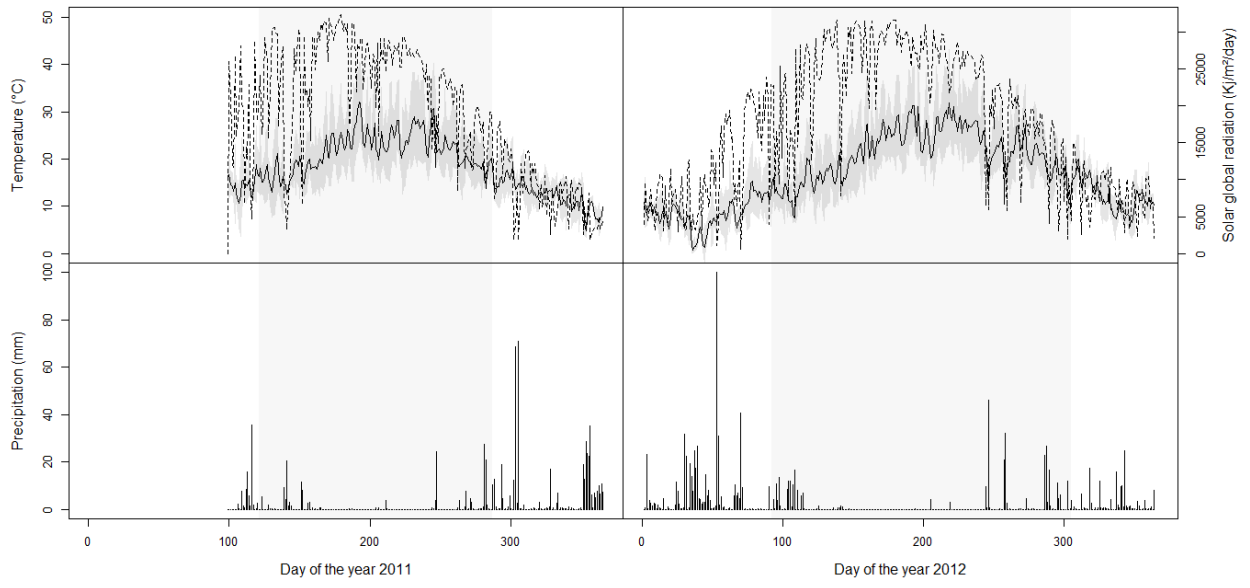
1 Figure legend:  
2 Figure1: Location of the Souk el Jema study site in Northern Tunisia.  
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4 Figure 2: daily time course of minimum, maximum and mean temperature (°C) (black  
5 line with grey shade), global solar radiation (KJ.m-2.day-1)(dotted line) and  
6 precipitation (mm) (histogram) registered at meteorological station in the Souk el Jema  
7 study site for years 2011 and 2012.  
8  
9 Figure 3: Daily soil water storage (mm) for layer 1 (0-5cm), layer 2 (5-15cm) and layer  
10 3 (15-45cm) registered from automated probes for EC (black line) and SD (dotted line)  
11 treatments for the rainfall exclusion period in 2011 and 2012. Daily precipitations are  
12 also shown.  
13  
14 Figure 4: A) Daily total soil water content (mm) (0-45cm) registered (black line) and  
15 simulated (dotted line) for the EC (a,b) and SD (e,f) for years 2011 and 2012, and leaf  
16 predawn water potentials (LWP +/- Standard Deviation) (MPa) measured for *Arbutus*  
17 *unedo* (black dots) and *Erica arborea* (empty dots) in the EC (c,d) and SD (g,h) and  
18 simulated (black line) with LAI values varying between 1.8 and 2.2 (grey shade). B)  
19 relationship between observed and measured predawn Leaf Water Potentials (*Arbutus*  
20 *unedo* black dots, *Erica arborea* empty dots) for EC and SD treatments for years 2011  
21 and 2012. R-square values, 1:1 line and regression line (dotted) are also shown.  
22  
23 Figure 5: Measured and simulated predawn leaf water potential (LWP) (MPa) for  
24 *Arbutus unedo* (black dots) and *Erica arborea* (empty dots) before and after the 30mm  
25 irrigation event on day of the year (DOY) 194 and the 3.8mm rainfall event on DOY 205  
26 in 2012.  
27  
28 Figure 6: Measured predawn leaf water potentials (LWP) (MPa) for *Arbutus unedo*  
29 (black dots) and *Erica arborea* (empty dots) and simulated LWP for total rainfall  
30 interception (SD H1) and experimental bias SD H2 (hypothesis that 20% rainfall reach  
31 the plot with shelters) and SD H3 (hypothesis SD H2 + lateral water movement in the  
32 deeper layer)  
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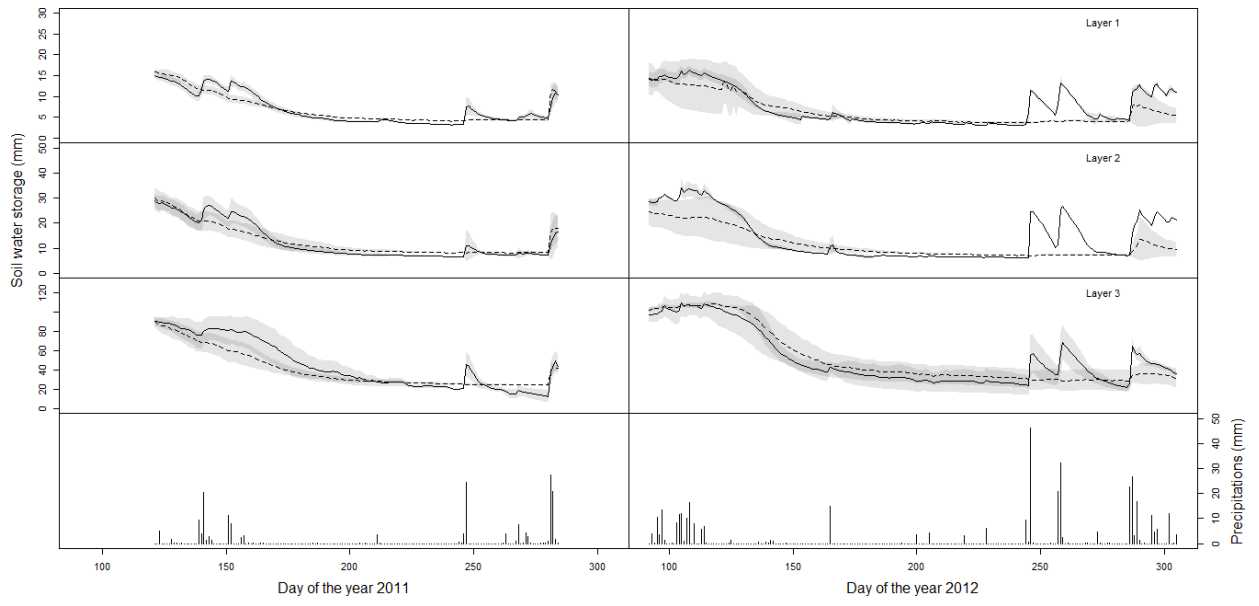
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1 Figure 2



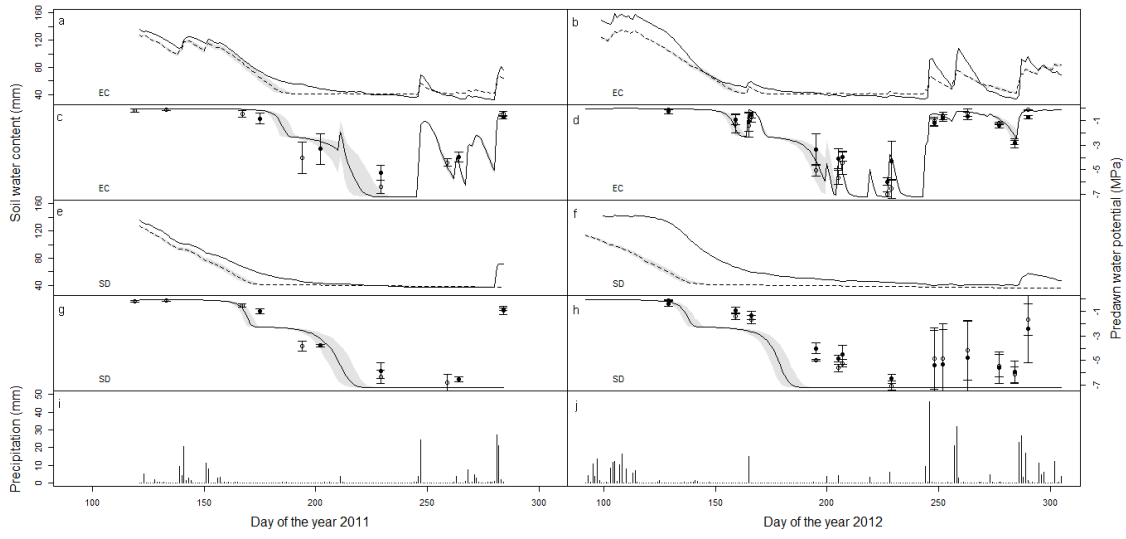
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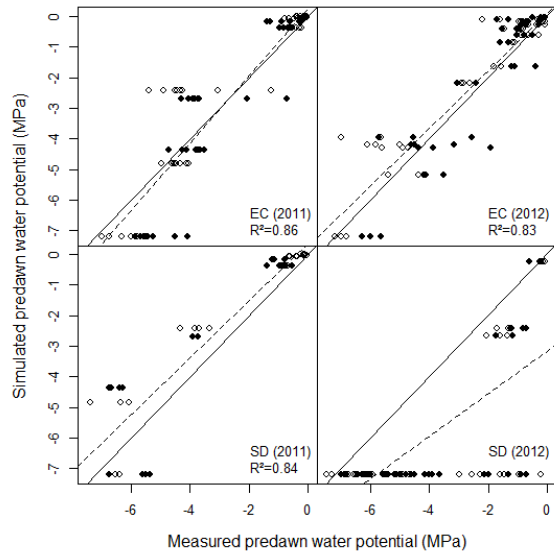


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1 **Figure 4**  
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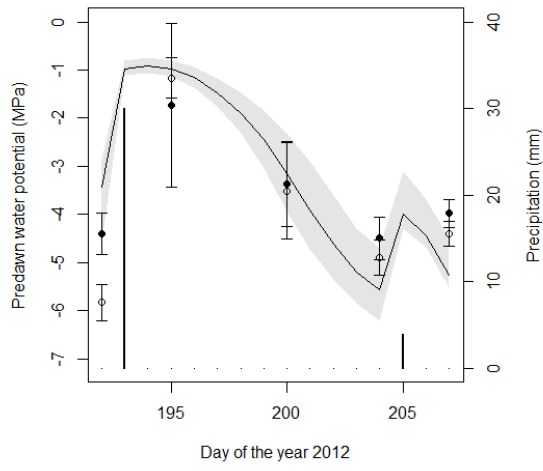


3 **B**  
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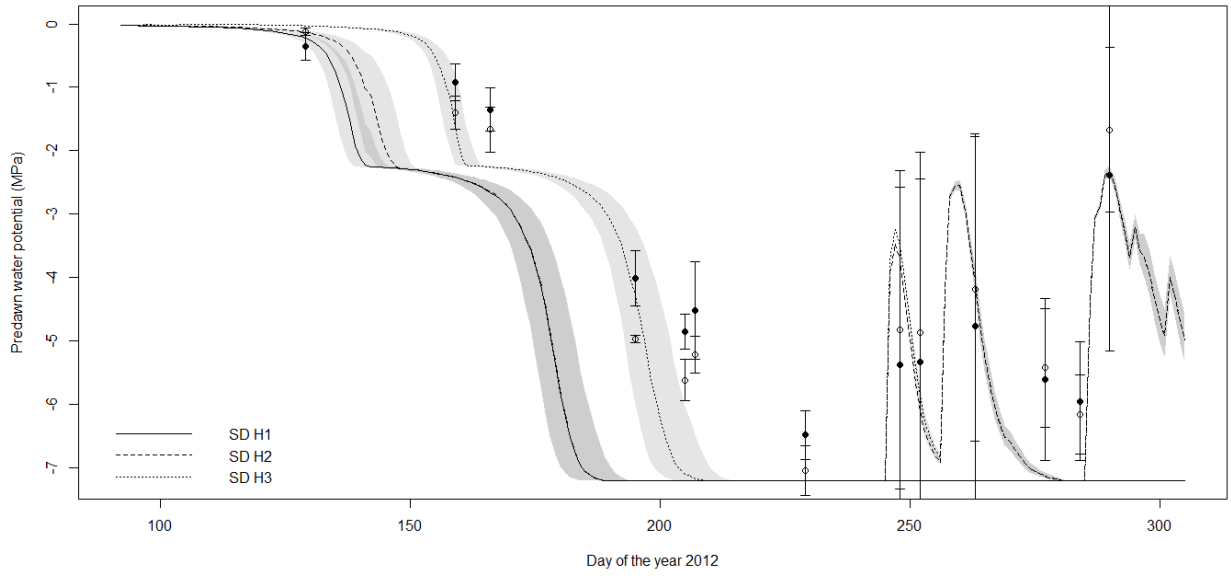
1 figure 5



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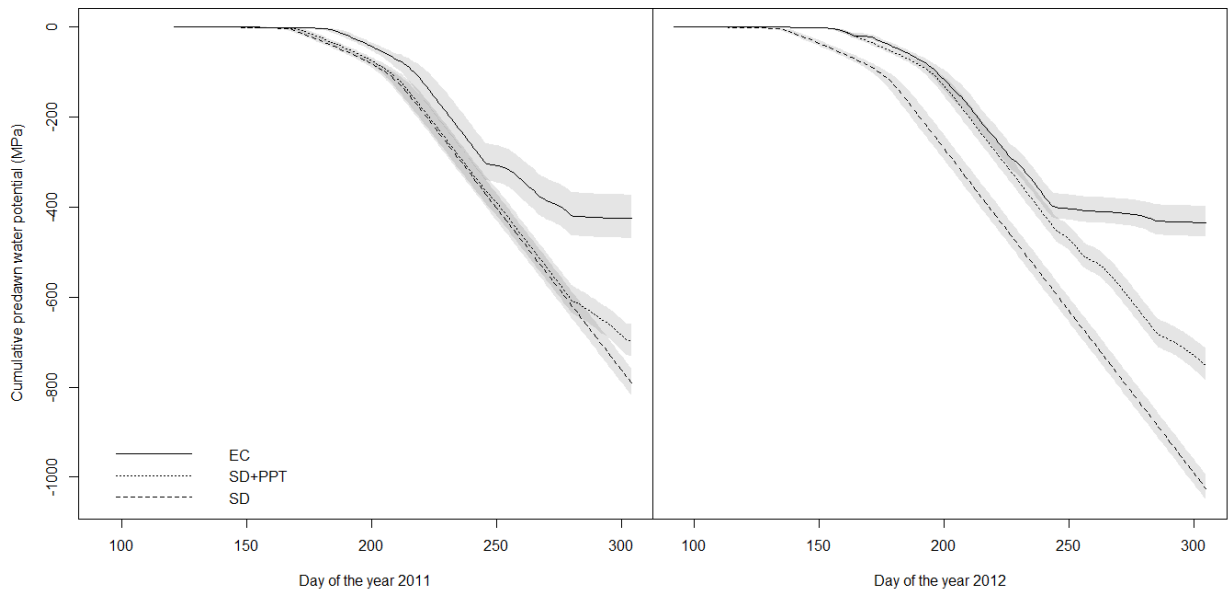


1 Figure 6



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1 Figure 7  
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