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1 **Soil water uptake and root distribution of different perennial and annual**  
2 **bioenergy crops**

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22 **Keywords**

23 bioenergy; energy crops; soil water; root system; miscanthus; switchgrass

24

25 **Abstract**

26 Background and aims

27 Bioenergy crops are expected to provide biomass as a replacement for fossil resources, but  
28 their impact on the water cycle is still under question. This study aimed at both quantifying  
29 the ability of bioenergy crops to use soil water and analysing the relationship between their  
30 root systems and soil water uptake.

31 Methods

32 Water content was monitored continuously for seven years (2007-2013) under perennial  
33 (*Miscanthus × giganteus* and *Panicum virgatum*), semi-perennial (*Festuca arundinacea* and  
34 *Medicago sativa*) and annual (*Sorghum bicolor* and *× Triticosecale*) bioenergy crops. Root  
35 distribution was characterized in 2010 down to 3 meters depth. Soil water deficit (SWD) was  
36 calculated as the difference between field capacity and actual water content.

37 Results

38 Maximal SWD (0-210 cm) during the growing season was higher for semi-perennials, despite  
39 a lower biomass production than perennials. Water capture in deep soil layers was greater  
40 under perennials and semi-perennials than under annual crops. A curvilinear asymptotic  
41 relationship was found between water capture and root density and described by a model the  
42 parameters of which varied between crops, indicating a variable soil water capture for a given  
43 root density.

44 Conclusions

45 This study provides quantitative information required to simulate the impact of bioenergy  
46 crops on drainage and aquifer loading.

47

48 **Abbreviations**

49 I: irrigation

50 P: precipitation

51 PET: potential evapotranspiration

52 PWC: proportional water capture

53 RID: root intersection density

54 RLD: root length density

55 RMSE: root mean square error

56 SWC: soil water content

57 SWD: soil water deficit

58

59 **Introduction**

60 In response to the challenges of climate change and depletion of fossil resources, biomass is  
61 expected to contribute significantly to the energy transition by providing renewable carbon for  
62 bioenergy, biomaterials and biochemicals (IPCC 2011; Ragauskas et al. 2006). Among  
63 biomass resources, dedicated bioenergy crops have large technical potential and will probably  
64 be a major player in the increase of bioenergy production (Bentsen and Felby 2012; Chum et  
65 al. 2011). The wide range of conversion technologies leads to a large diversity of candidate  
66 crops: short rotation coppices, perennial crops, semi-perennial forage crops and annual crops  
67 (Karp and Shield 2008; Lewandowski et al. 2003; Sanderson and Adler 2008; van der Weijde  
68 et al. 2013; Zegada-Lizarazu and Monti 2011).

69 Perennial C4 rhizomatous crops like *Miscanthus × giganteus* (hereafter referred to as  
70 miscanthus) or *Panicum virgatum* (hereafter referred to as switchgrass) are considered as  
71 promising energy crops because of their high biomass production, low nutrient requirements

72 and low greenhouse gas emissions (Cadoux et al. 2014; Don et al. 2011; Somerville et al.  
73 2010). However, large deployment of these crops could modify their regional environment.  
74 One particular concern is the effect on the water cycle through modifications in  
75 evapotranspiration (McIsaac et al. 2010; Vanloocke et al. 2010). Several authors have  
76 suggested that perennial bioenergy crops consume more water than annual crops, because of  
77 their higher biomass production, longer growing period and deeper root system (Heaton et al.  
78 2010; Powlson et al. 2005; Rowe et al. 2009). Using soil moisture measurements over four  
79 growing seasons in central Illinois, McIsaac et al. (2010) estimated that miscanthus had higher  
80 evapotranspiration than switchgrass and maize-soybean rotation. Hickman et al. (2010) found  
81 similar results at the same site during one growing season by using a micrometeorological  
82 method. Using a model-based approach, Le et al. (2011) predicted an average 58% and 36%  
83 increase of total seasonal evapotranspiration for miscanthus and switchgrass respectively,  
84 compared to maize in the Midwest United States. This higher water consumption during crop  
85 growth will reduce the amount of water drained during winter. Vanloocke et al. (2010)  
86 predicted with a dynamic global vegetation model a decrease in drainage ranging from 50 to  
87 250 mm yr<sup>-1</sup> with miscanthus cultivation instead of current land cover for the Midwest United  
88 States. This decrease of drainage is likely to impact aquifers in case of large-scale land  
89 conversions.

90 Among factors influencing crop water use, morphology and distribution of roots within the  
91 soil profile are of prime importance because they define the amount of water that can be  
92 supplied to the crop (Jackson et al. 2000). Deep rooting (> 2 m) has been reported by several  
93 authors for miscanthus and switchgrass (Ma et al. 2000; Neukirchen et al. 1999; Riche and  
94 Christian 2001). This extensive root system may allow these crops to maintain their growth in  
95 case of drought period but is also likely to lead to a greater soil water deficit (SWD) than  
96 annual crops at the end of the growing season (Riche and Christian 2001). To our knowledge,

97 only one study has compared soil water uptake and root distribution of different bioenergy  
98 crops (Monti and Zatta 2009). However this study was restricted to one growing season and  
99 the soil sampling depth was only 120 cm. There is a need to compare a wide range of  
100 candidate bioenergy crops over multiple seasons to take into account climate variability and in  
101 a deep soil to maximize the differences in root distribution between crops.

102 We hypothesized that perennial C4 crops use deep soil water resources because of their  
103 extensive root system and high biomass production, leading to a higher SWD than with other  
104 crops. The aim of this study was (1) to quantify soil water utilization for perennial, semi-  
105 perennial and annual bioenergy crops using a long term and continuous monitoring of soil  
106 water, and (2) to study the relationship between the root system of the crops and soil water  
107 uptake.

108

## 109 **Materials and methods**

### 110 Study site and experimental design

111 This study is based on an ongoing long-term experiment carried out by INRA at the  
112 experimental station of Estrées-Mons, northern France (49.872°N, 3.013°E), on a Haplic  
113 Luvisol (IUSS Working Group WRB 2006). The experiment was initiated in 2006 and six  
114 crops were compared, representing a wide range of bioenergy crop types: two perennial C4  
115 crops, two semi-perennial forage crops and two annual crops. The chosen crops were  
116 miscanthus (*Miscanthus×giganteus* Greef & Deuter ex Hodkinson & Renvoize), switchgrass  
117 (*Panicum virgatum* cv. Kanlow), fescue (*Festuca arundinacea* cv. Dulcia from 2006 to 2008,  
118 Noria from 2009 to 2010 and Bariance after 2010), alfalfa (*Medicago sativa* cv. Alpha from  
119 2006 to 2008, Orca from 2009 to 2010 and Salsa after 2010), fibre sorghum (*Sorghum bicolor*  
120 (L.) Moench cv. H133) and triticale ( $\times$  *Triticosecale* Wittmack cv. Triskell from 2006 to  
121 2008, Amarillo from 2009 to 2011 and Tarzan after 2011). The annual crops were grown in

122 rotation (triticale grown after sorghum and *vice-versa*) as well as the semi-perennial crops  
123 (alfalfa grown after fescue and *vice-versa*) and all crops were present each year. A catch crop  
124 was sown every year in August or early September between triticale and sorghum (rye in  
125 2007, mustard in 2008, oat-vetch mixture in 2009 and mustard-clover mixture from 2010 to  
126 2013). The perennial crops were established in 2006 and the semi-perennial crops were sown  
127 in 2006 (first rotation), 2009 (second rotation) and 2011 (third rotation). Two harvest dates  
128 were compared for miscanthus and switchgrass: an early harvest in October and a late harvest  
129 in February. The experiment also included two nitrogen treatments for each crop except  
130 alfalfa, with a plot size of 360 m<sup>2</sup> and three replicates per treatment. Details about crop  
131 management and experimental treatments are given by Cadoux et al. (2014). In this study, we  
132 selected experimental treatments maximizing plant growth and thus water consumption: the  
133 late harvest for miscanthus and switchgrass and the highest nitrogen treatment for all crops.  
134 During the period 2007-2013, the mean N fertilization rates for the selected treatments were  
135 120 kg ha<sup>-1</sup> yr<sup>-1</sup> for miscanthus, switchgrass, sorghum and triticale, 170 kg ha<sup>-1</sup> yr<sup>-1</sup> for fescue  
136 and 0 for alfalfa. The experiment did not receive irrigation, except in May 2011 for fescue,  
137 alfalfa, sorghum and triticale (58 mm in total) to facilitate crop establishment during a drought  
138 period.

139

#### 140 Climatic data

141 Climatic data were obtained from an automatic weather station situated on the experimental  
142 site. Over the period 2007-2013, mean temperature was 10.6 °C, annual rainfall (P) and  
143 Penman potential evapotranspiration (PET) were 686 and 714 mm respectively and annual  
144 global radiation was 4154 MJ m<sup>-2</sup>. The water balance (P-PET) during the growing season  
145 displayed a rather large variability between years (Table 1). We considered March 1 as the  
146 beginning of the growing season because it corresponds approximately to the time when

147 winter crops like triticale start growing again and PET begins running higher than 1 mm d<sup>-1</sup>.  
148 We considered November 1 as the end of the growing season because all annual and semi-  
149 perennial crops have been harvested and perennials are close to total senescence. The wettest  
150 year was 2008 and 2009 was the driest, with only 116 mm of precipitation from June to  
151 September. Springs 2010 and 2011 were drier than the seven-year average.

152

### 153 Biomass production

154 The aboveground biomass at harvest was estimated for each crop. At each harvest date, plants  
155 were harvested manually and weighed. Miscanthus and switchgrass were harvested in  
156 February or early March. Fescue and alfalfa were harvested in two or three cuttings depending  
157 on the years, with the last cut in October. Sorghum was harvested in late September and  
158 triticale in late July or early August. Details about sampling methodologies are given by  
159 Cadoux et al. (2014). The dry matter content was determined after drying representative  
160 subsamples at 65°C for 96 h. The biomass production was expressed in tons of dry matter per  
161 hectare and per year for all crops.

162

### 163 Soil and soil water monitoring

#### 164 Measurements

165 We used water content reflectometers (Campbell Scientific CS616) to monitor the soil  
166 moisture profile continuously from July 2007 to November 2013. Probes were installed in  
167 May 2007 in six plots (one plot per crop), inserted horizontally into the soil at 15, 45, 75, 105,  
168 135, 165 and 195 cm depth (three replicates at 15 cm depth and two replicates at the other  
169 depths). Temperature sensors (Campbell Scientific 107) were also placed at 15 and 195 cm  
170 depth. Data were recorded at an hourly time step using CR1000 Campbell Scientific data



171 loggers. Probes placed at 15 cm depth were removed for soil tillage and reinserted as soon as  
172 possible.

173 Soil cores taken down to 210 cm from the six plots in 2006 were analysed to determine soil  
174 characteristics which were very homogeneous in the six plots (Table 2). Bulk density was  
175 measured at each CS616 depth in May 2007 using steel cylinders of 98 cm<sup>3</sup> (5 cm diameter,  
176 three replicates) and measurements were repeated for the upper depth (15 cm) in 2010 and  
177 2011 or 2012 with six replicates. Gravimetric water content was measured in the three blocks  
178 twice a year (in mid-March and early November) from 2007 to 2013. At each date of  
179 measurement, soil cores were collected down to a depth of 150 cm with a driller 18 mm in  
180 diameter. The cores were divided into five layers (0-30, 30-60, 60-90, 90-120 and 120-150  
181 cm). In each soil layer, one soil sample was formed by mixing five soil cores for each plot. In  
182 the instrumented plots, additional measurements were made during summer 2009 and from  
183 November 2011 to November 2013 down to 210 cm, with three individual cores per plot  
184 divided into seven layers. Only gravimetric measurements made in the instrumented plots  
185 were used to calibrate CS616 probes.

#### 186 Data processing and calculations

187 Data from CS616 probes need proper correction and calibration in order to obtain accurate  
188 soil moisture measurements (Rudiger et al. 2010). First of all, data were regularly collected in  
189 a database managed with PostgreSQL and eventual outliers were eliminated. Secondly, the  
190 soil temperature was simulated at each CS616 depth using a script developed with R software  
191 (R Core Team 2014). We used Fourier's law to simulate heat conduction transfer through the  
192 soil profile. Soil temperature at 15 and 195 cm depth were taken as boundary conditions and  
193 the initial temperature along the soil profile was determined by linear interpolation between  
194 the two depths. Depth and time increments as well as thermal diffusivity (*alpha*) were  
195 optimized using two other plots of the same experiment with supplementary soil temperature

196 measurements at 75 and 135 cm depth. The optimized value for *alpha* was  $24 \text{ cm}^2 \text{ h}^{-1}$  and the  
197 root mean square error (RMSE) was  $0.2^\circ\text{C}$  over a period of 434 days. Thirdly, period  
198 measurements from the CS616 probes were corrected for measured or simulated soil  
199 temperature, using the temperature correction equation provided by Rudiger et al. (2010) with  
200 the slope coefficient for silt loam. The fourth step consisted in deriving a relationship between  
201 corrected period measurements and volumetric soil water contents, obtained from gravimetric  
202 water contents and bulk density measurements. A covariance analysis was applied with R  
203 software for the two or three replicates of each plot and depth in order to choose (with a 95%  
204 confidence level) between an individual calibration with a specific linear regression equation  
205 for each replicate, a common calibration or an individual calibration of the intercept with a  
206 common slope. The mean coefficient of determination was 0.86 for the 90 probes ( $n=17$ ) and  
207 the mean RMSE was  $0.016 \text{ cm}^3 \text{ cm}^{-3}$ . Finally, all corrected period measurements were  
208 converted into volumetric and gravimetric water content and the two or three replicates were  
209 averaged. Missing data were filled in by linear interpolation and data were aggregated to  
210 obtain daily measurements. Standard deviation between replicates was, on average over the  
211 period 2007-2013,  $0.019 \text{ cm}^3 \text{ cm}^{-3}$  for the first layer (3 replicates) and  $0.007 \text{ cm}^3 \text{ cm}^{-3}$  for the  
212 other layers (2 replicates).

213 The soil water content (SWC, in mm) was calculated in each 30 cm soil layer and summed up  
214 over the monitored soil profile (0-210 cm). For each crop, SWC calculated over the three  
215 replicated plots with gravimetric measurements were compared to SWC calculated in the  
216 single instrumented plot using CS616 probes. We found a good, unbiased relationship  
217 between the two estimates ( $y = 1.005 x$ ;  $R^2=0.94$ ;  $n=65$ ), which indicated that SWC assessed  
218 with CS616 probes were representative of the whole field. The soil water deficit (SWD, in  
219 mm) was defined as the difference between SWC at field capacity and the measured SWC  
220 (Beale et al. 1999) for each soil layer or over the monitored soil profile. For each soil layer,

221 the proportional water capture (PWC, in %) was calculated as the fraction of potentially  
222 available water that had been captured by plant roots (Monti and Zatta 2009):

$$223 \quad PWC = \frac{SWC_{FC} - SWC}{SWC_{FC} - SWC_{WP}} \cdot 100 \quad (1)$$

224 where  $SWC_{FC}$  is the water content at field capacity (in mm) and  $SWC_{WP}$  the water content at  
225 permanent wilting point (in mm).  $SWC_{FC}$  was calculated as the median of the gravimetric  
226 measurements made in winter (March) over the period 2007-2013.  $SWC_{WP}$  was measured  
227 with Richard's pressure plates at -1.5 MPa water potential.

228

### 229 Root mapping

230 We collected data on root distribution during the year 2010 for each plot in which soil water  
231 was monitored using a modified trench profile method (Tardieu 1988). First of all, a trench  
232 300 cm deep was dug into the plot. The observed vertical profile (180 cm wide, 300 cm deep)  
233 which was perpendicular to the crop row was then prepared. After the working surface had  
234 been smoothed, roots were made visible by removing approximately 1 cm of soil with a  
235 knife. Next, roots were mapped on three adjacent 60 \* 300 cm grids with cells of 1.9 \* 1.9  
236 cm. Since root counting was a very time-intensive operation, the number of root impacts in  
237 each cell was measured only on 20% of the cells for each 60 cm wide grid (the seven cells at  
238 the right of the grid), and the presence or absence of root impact was noted for the other cells.  
239 The distribution of roots was recorded on 11 and 25 June 2010 for miscanthus and  
240 switchgrass respectively (4-year-old crops), on 14 and 21 September 2010 for fescue and  
241 alfalfa respectively (1.5-year-old crops), on September 9, 2010 for sorghum (at the beginning  
242 of anthesis) and on July 13, 2010 for triticale (ten days before physiological maturity).

243

### 244 Relationship between root density and proportional water capture

245 In studies dealing with roots and water uptake, the root distribution is often described using  
246 the root length density (RLD), i.e. the total root length per unit of soil volume (Gregory  
247 2006). Experimental measurement of RLD by extracting soil cores or soil monoliths can be  
248 extremely labour-intensive. Mapping and counting root impacts on a vertical soil profile has  
249 the advantage of being easier to do in the field but provides no direct measurement of RLD.  
250 However, the root intersection density (RID), i.e. the mean number of root impacts per cm<sup>2</sup>  
251 (Chopart et al. 2008), can be calculated from such measurements and linear relationships  
252 between RID and RLD have been found for various crops (Chopart et al. 2008; Chopart and  
253 Siband 1999; Dusserre et al. 2009). We therefore assumed that RID could be used as an  
254 indicator of RLD. Indeed, we also determined RLD for miscanthus and switchgrass (Ferchaud  
255 et al. 2012) and verified the linear relationship between RLD and RID for these two crops.

256 RID was calculated in each 60 \* 300 cm grid for each layer of 30 cm thickness.

257 The relationship between RID and water capture was studied in 2010 using PWC calculated at  
258 the date of the maximal soil water deficit (over 0-210 cm). The relationship was described for  
259 each crop with a model derived from King et al. (2003):

$$260 \quad PWC = (a - y_0) \cdot (1 - e^{-k \cdot RID}) + y_0 \quad (2)$$

261 where  $k$  is a “resource capture coefficient” which summarizes details of water uptake  
262 physiology and soil water transport. A higher  $k$  value leads to a faster increase in water  
263 extraction when root density increases. Compared to the original model of King et al. (2003),  
264 we added two parameters:  $a$  which is the highest PWC achievable by the crop ( $a = 100\%$  in  
265 the original model) and  $y_0$  which is the PWC obtained in free root soil layers due to possible  
266 water capillary rise ( $y_0 = 0$  in the original model). A common value for all crops was chosen  
267 for  $y_0$ . The parameter optimization for  $a$  and  $k$  was realised with the Excel solver using the  
268 GRG nonlinear method. The minimized criterion was the RMSE.

269

## 270 Statistical analysis

271 All statistical analyses were performed with R (R Core Team 2014). The effect of the crop on  
272 highest and lowest SWC of each year was evaluated by one-factor analysis of variance  
273 (ANOVA), using the different probes as replicates. We used a two-factor ANOVA without  
274 replication with crop and year as factors in order to test the crop effect on mean SWD for each  
275 soil layer and for 0-210 cm. For PWC, we included the soil layer as third factor. For RID, the  
276 effect of the crop was evaluated in each layer by one-factor ANOVA, using the three adjacent  
277 grids as replicates. Differences between crops were evaluated with Tukey's HSD (honest  
278 significant difference) test for all variables. The assumptions of ANOVA were checked by  
279 visual examination of the residuals against predicted values and using Shapiro-Wilk and  
280 Levene's tests. If necessary, we used square root transformation or arcsine square root  
281 transformation to satisfy these assumptions.

282

## 283 **Results**

### 284 Soil water content

285 SWC over the soil profile (0-210 cm, measured with CS616 probes) fluctuated over the  
286 seven-year period with a regular pattern for all crops (Fig. 1). It was at its highest level in  
287 winter (above 700 mm), decreased every year during spring and summer and rose in autumn.  
288 SWC in winter was rather stable between years and crops. It was close to the estimated SWC  
289 at field capacity (mean = 730 mm) and peaked from time to time at approximately 750 mm.  
290 Differences in maximum SWC between crops were only significant three years out of six. In  
291 2009-2010 and 2010-2011, SWC did not reach field capacity for several crops (miscanthus  
292 and switchgrass in 2009-2010, miscanthus, switchgrass, fescue and alfalfa in 2010-2011).  
293 Indeed, in these cases, autumn and winter precipitations were not sufficient for the deeper  
294 layers to reach field capacity. The timing of SWC decrease depended on the crops, with an

295 earlier decline for triticale, fescue and alfalfa (except in 2009 and 2011 when these two crops  
296 were newly sown) than for the other crops. The lowest SWC over a year were observed on  
297 average over the period 2007-2013 in mid-October for miscanthus, in mid-September for  
298 switchgrass, fescue, alfalfa and sorghum and in early July for triticale. Minimal SWC were  
299 more variable between years and crops than maximal SWC. Differences in minimal SWC  
300 between crops were significant every year, with a range of variation between crops higher  
301 than 100 mm five years out of seven. The lowest SWC over the period 2007-2013 were  
302 observed in 2009 for all crops except for triticale, for which the lowest SWC was observed in  
303 2013. These values (433 mm for alfalfa, 451 mm for fescue, 495 mm for switchgrass, 507 mm  
304 for sorghum, 526 mm for miscanthus and 528 mm for triticale) were significantly higher than  
305 the estimated SWC at permanent wilting point (mean = 318 mm). The timing of SWC  
306 increase after this minimal point was more stable between crops than the timing of SWC  
307 decrease in spring, but generally faster for annual crops than for the other crops.

308

#### 309 Maximal soil water deficit

310 In order to quantify soil water utilization by the crops, we calculated the maximal SWD each  
311 year over the soil profile (0-210 cm), corresponding to the minimal SWC for the year.  
312 Maximal SWD ranged from 61 mm for triticale in 2007 to 294 mm for alfalfa in 2009. For  
313 each crop, the variability of the maximal SWD between years was large, with standard  
314 deviations of 41 to 59 mm. Nevertheless, alfalfa had the largest maximal SWD six years out  
315 of seven and fescue always had the second largest maximal SWD. The ranking of other crops  
316 was more variable between years. On an average, over the period 2007-2013, the differences  
317 between crops were significant (Fig. 2). Alfalfa had a higher maximal SWD (218 mm) than  
318 the other crops except fescue. Maximal SWD was lowest for sorghum (142 mm) and  
319 intermediate for triticale, miscanthus and switchgrass (156, 157 and 171 mm respectively).

320 At maximal SWD, SWD calculated in each soil layer was higher in the topsoil (Fig. 2). On an  
321 average, 47% of the total SWD was located in the upper two layers (0-60 cm), 38% in the  
322 three intermediate layers (60-150 cm) and only 15% in the two deeper layers (150-210 cm).  
323 However, this distribution was crop-dependent: annual crops had a higher proportion of the  
324 total SWD in the 0-60 cm layer (56%) and a lower proportion in the 150-210 cm layer (11%)  
325 than the other crops. SWD in the 150-210 cm layer was 16 mm for sorghum and triticale,  
326 significantly lower than alfalfa (46 mm). SWD in the first layer (0-30 cm) was significantly  
327 lower for miscanthus and switchgrass (44 and 35 mm respectively) than for fescue, alfalfa and  
328 triticale (66, 56 and 56 mm respectively).

329 We examined the influence of climate conditions on maximal SWD. Using data of  
330 precipitation (P), irrigation (I) and potential evapotranspiration (PET), the water balance (P+I-  
331 PET) was calculated each year and for each crop from March 1 to the date of maximal SWD.  
332 The water balance was -238 mm on an average and was very similar for most crops ( $-256 \pm 5$   
333 mm), except for triticale (-148 mm). It was negatively correlated with maximal SWD ( $r = -$   
334  $0.63$ ;  $p < 0.001$ ; Fig. 3).

335 The influence of aboveground biomass production on maximal SWD was also investigated.  
336 No significant correlation was found between biomass production and maximal SWD (Fig. 4).  
337 This was true not only when all crops were grouped together but also for each crop  
338 independently, despite large differences in biomass production between crops and years for  
339 some crops. Miscanthus, switchgrass and triticale had a rather stable biomass production over  
340 the period 2007-2013 but fescue, alfalfa and sorghum displayed a higher variability with low  
341 biomass production ( $< 10 \text{ t ha}^{-1}$ ) some years. Surprisingly, the highest maximal SWD (-294  
342 and -275 mm for alfalfa and fescue respectively) was observed for low biomass production  
343 ( $3.2$  and  $6.4 \text{ t ha}^{-1}$ ) during the year 2009, which was the driest year and when fescue and  
344 alfalfa were newly sown. The biomass production of catch crops grown between triticale and

345 sorghum was not taken into account because it was very low ( $0.5 \pm 0.2$  t DM ha<sup>-1</sup> on average  
346 over the period 2007-2013).

347

348 Proportional water capture

349 PWC was calculated for each year and each soil layer at the date of the maximal SWD. Crops,  
350 soil depth and their interaction significantly affected PWC. On average, PWC decreased with  
351 depth from 74% in the 0-30 cm layer to 19% in the 180-210 cm layer, and never reached  
352 100% below 30 cm. However, differences between crops were significant for all soil layers  
353 (Fig. 5). For the first soil layer (0-30 cm), PWC was significantly lower for miscanthus and  
354 switchgrass than for other crops. The highest PWC observed in the 0-30 cm layer over the  
355 period 2007-2013 was only 76% and 57% for miscanthus and switchgrass respectively,  
356 compared to 100% for the other crops. The differences between crops were smaller in the 30-  
357 60 and 60-90 cm layers, with a higher PWC for fescue and alfalfa. PWC was smaller for  
358 sorghum and triticale below 90 cm. Alfalfa had the highest PWC (42% and 33% on average)  
359 in the 150-180 and 180-210 cm layers respectively. It was significantly higher than for  
360 sorghum and triticale (15% and 16% in the 150-180 cm layer; 12% and 11% in the 180-210  
361 cm layer, respectively). The variability of PWC between years was smaller in deeper than in  
362 upper layers for annual crops, but not for other crops.

363 PWC calculated at the date of maximal SWD were compared to PWC calculated at the end of  
364 the growing season, i.e. November 1 (data not shown). PWC changed very slightly for the  
365 three deeper layers (only 1% on average) but was reduced in the upper layers. This means that  
366 there was no or very little additional water retrieval in the deeper layers after the date of  
367 maximal SWD, even for crops for which maximal SWD was observed on average more than  
368 one month before the end of their growing period (switchgrass, fescue, alfalfa).

369



370           Root distribution and root intersection density

371 Fig. 6 shows the root distribution of each crop observed in 2010 on the trench profiles.  
372 Miscanthus, switchgrass and alfalfa had a particularly deep root system: the maximum rooting  
373 depth was 300, 288 and 276 cm respectively. Sorghum had a more superficial root system  
374 (maximum rooting depth = 128 cm) and fescue and triticale were intermediate with a  
375 maximum rooting depth of 200 cm. The proportion of cells including roots decreased with  
376 depth, more or less according to the crops. This proportion decreased from 79% (sorghum) to  
377 100% (fescue) in the 0-30 cm layer down to 0% (sorghum) to 10% (miscanthus) in the 180-  
378 210 cm layer. For the crops with a maximum rooting depth exceeding 210 cm, the proportion  
379 of cells including roots in the 210-300 cm layer was 7, 1 and 4% respectively for miscanthus,  
380 switchgrass and alfalfa.

381 Root intersection density (RID) decreased drastically with depth for all crops (Table 3). It  
382 varied from 0.57 (sorghum) to 1.17 roots cm<sup>-2</sup> (fescue) in the 0-30 cm layer, and became  
383 lower than 0.04 roots cm<sup>-2</sup> for all crops in the 180-210 cm layer. The crop effect was  
384 significant in all soil layers. RID was significantly higher for fescue than sorghum, alfalfa and  
385 miscanthus in the first layer and higher for fescue, alfalfa and switchgrass than for miscanthus  
386 and sorghum in the 30-60 and 60-90 cm layers. In the 150-180 and 180-210 cm layers,  
387 miscanthus, switchgrass and alfalfa had a significantly higher RID than sorghum and triticale.  
388 Over 0-210 cm, the mean RID was 0.15 and 0.18 roots cm<sup>-2</sup> respectively for sorghum and  
389 miscanthus, 0.24 and 0.26 roots cm<sup>-2</sup> respectively for triticale and alfalfa and 0.30 and 0.32  
390 roots cm<sup>-2</sup> respectively for switchgrass and fescue. Only miscanthus, switchgrass and alfalfa  
391 produced roots below 210 cm, with a significantly lower RID for switchgrass.

392

393           Relationship between root distribution and water uptake

394 We studied the relationship between RID measured in 2010 and PWC calculated for each soil  
395 layer at the date of the maximal SWD in 2010. Maximal SWD occurred on July 11 for  
396 triticale, on August 15 for switchgrass, fescue, alfalfa and sorghum and on October 31 for  
397 miscanthus. The year 2010 was the second driest year during the growing season, after 2009.  
398 PWC were therefore higher during year 2010 than the average for all crops at almost all  
399 depths.

400 A positive linear correlation was found between RID and PWC for all species ( $r = 0.72$ ;  $p <$   
401  $0.001$ ). However, the relationship was not strictly linear but rather curvilinear asymptotic and  
402 differences appeared between crops (Fig. 7). The highest PWC found in the 0-30 cm layer  
403 varied widely between crops, from 53% for switchgrass to 100% for fescue and triticale  
404 whereas the corresponding RID was similar for most crops. This was also true for the deeper  
405 soil layers where a large variability in PWC was observed for identical RID. The model  
406 derived from King et al. (2003) was fitted for each crop independently (Fig. 7). Water capture  
407 was observed for sorghum in the layers 150-180 cm and 180-210 cm (PWC = 14 and 10%  
408 respectively), although no visible root was found in these layers. We used the mean of these  
409 two values (12%) for the  $y_0$  parameter for all crops. Simulated PWC were in good agreement  
410 with observed data, with a mean RMSE of 7% (Table 4). The goodness of fit was equivalent  
411 for all crops except for fescue, which had the highest RMSE. The parameter values obtained  
412 after optimization were rather variable between crops (Table 4). The “resource capture  
413 coefficient”  $k$  was highest for fescue, followed by switchgrass and alfalfa and smaller for  
414 sorghum and triticale. Annual crops were characterized by an  $a$  value (highest PWC  
415 achievable by the crop) greater than for other crops, particularly perennials.

416

## 417 **Discussion**

418

419           Soil water deficit and water capture

420 Few studies have compared the evolution of soil water content during the growing season for  
421 different bioenergy crops. For example, alfalfa has been compared to annual crops (Entz et al.  
422 2001) but not to fescue or perennial C4 crops. Our study is the first one comparing perennial,  
423 semi-perennial and annual bioenergy crops. Entz et al. (2001) found that soil water content  
424 during summer (over 0-150 cm) was always lower for alfalfa than for annual crops during five  
425 years of cultivation. This is consistent with our study showing that the highest maximal SWD  
426 was observed for alfalfa six years out of seven. The differences in maximal SWD over 0-210  
427 cm between miscanthus, switchgrass and annual crops were small and not significant in our  
428 study with a different ranking according to the year. McIsaac et al. (2010), who monitored  
429 soil moisture under miscanthus, switchgrass (cv. Cave-In-Rock) and a maize-soybean  
430 rotation, also found contrasting results between growing seasons. They found that the minimal  
431 soil moisture under miscanthus and switchgrass was either equal (two years out of four) or  
432 lower (the other two years) than under annual crops. However, in contrast to our results, they  
433 observed that miscanthus resulted in lower minimal soil moisture than switchgrass during the  
434 four growing seasons.

435 We found that maximal SWD was correlated to the water balance (P+I-PET) but not to the  
436 aboveground biomass production. The biomass production of the semi-perennial crops was  
437 only 57% of the miscanthus production and 64% of the switchgrass production but their  
438 maximal SWD was higher. In fact, maximal aboveground biomass of perennial crops (in  
439 October) was even higher than the biomass at harvest (in February) due to leaf fall during  
440 winter (only for miscanthus) and carbon transfer from aboveground to belowground parts in  
441 autumn (Dohleman et al. 2012; Strullu et al. 2011). This suggests that miscanthus and  
442 switchgrass had higher water use efficiency than fescue and alfalfa. Beale et al. (1999)  
443 calculated water use efficiencies for miscanthus in UK with the maximal aboveground

444 biomass reached by the crop during the growing season. They found comparable values to  
445 other C4 crops, such as maize, and higher values than C3 crops such as willow. Furthermore,  
446 it is possible that the timing of the growing periods of the crops affects water use efficiency  
447 due to differences in climate conditions. The lack of correlation between maximal SWD and  
448 aboveground biomass production observed during the seven years for each crop  
449 independently indicates that SWD was much more sensitive to the water balance than biomass  
450 production.

451 Our results also indicate that perennial C4 crops and semi-perennial forage crops, and  
452 particularly alfalfa, have the ability to take up significant amounts of water in deep soil layers  
453 (150-210 cm). Water uptake is even likely to occur below 210 cm for miscanthus, switchgrass  
454 and alfalfa since these crops have roots deeper than 210 cm. Our results are in agreement with  
455 Campbell et al. (1994) and Dardanelli et al. (1997) who showed that alfalfa growing in deep  
456 soil can withdraw water to a depth of 250 cm, and Finch and Riche (2008) who found  
457 significant soil water depletion down to 170 cm with miscanthus at two sites in England.

458 However, the ability of miscanthus and switchgrass to take up deep soil water did not lead to  
459 a significantly higher maximal SWD than annual crops because it was compensated by a  
460 lower SWD in the 0-30 cm layer. This lower SWD near the soil surface, which had not been  
461 emphasized in previous studies, was at least partly due to lower soil evaporation. Indeed,  
462 these two crops have a high and dense canopy during summer, when PET is maximal, which  
463 is likely to limit soil evaporation. Furthermore, the fallen leaves of miscanthus accumulating  
464 at the soil surface form a 2-4 cm thick mulch (Amougou et al. 2012) which enhances the  
465 reduction of soil evaporation.

466

467           Root distribution

468 We assumed that our protocol was appropriate to compare the root systems of the different  
469 crops. The root systems of annual crops measured at anthesis or post-anthesis were probably  
470 close to maximal development (Hoad et al. 2001; Zhang et al. 2004). Root distribution of  
471 perennial and semi-perennial crops was recorded at two periods during the year 2010 (June  
472 and September respectively). Root extension of perennial crops had probably reached steady  
473 state since the crops were 4 years old. Neukirchen et al. (1999) did not find any effect of the  
474 sampling date on root density when comparing three dates of measurements in a 5-year-old  
475 miscanthus. Semi-perennials were at the end of their second year of growth at the time of  
476 measurement: the recorded root distribution corresponded to well-established crops and was  
477 probably close to the maximal root development achieved during the 2010 growing season  
478 although we do not know if it was at steady state. The climate conditions in 2010, with a first  
479 part of the growing season (March-June) drier than the average, might have affected root  
480 development of annual and semi-perennial crops. However, this is unlikely because the  
481 available soil water was high in March (240 mm over 0-120 cm) and the biomass of these  
482 crops in 2010 was similar to the average (104% of the 2007-2013 mean biomass production).  
483 In our conditions, i.e. in a deep loamy soil with no obstacles to rooting, crops exhibited large  
484 differences in rooting depth. Miscanthus, switchgrass and alfalfa had a particularly deep root  
485 system. The maximal rooting depth of miscanthus ( $\geq 300$  cm) was deeper than that recorded  
486 in other field experiments: 200 cm for a 6-year-old crop in a silty clay loam in England (Riche  
487 and Christian 2001) and 250 cm for a 3-year-old crop in a sandy loam in Germany  
488 (Neukirchen et al. 1999). The difference with our study might result from differences in soil  
489 characteristics or maximum depth of observation. The maximum rooting depth of switchgrass  
490 measured in our experiment (288 cm) was intermediate between that observed by Riche and  
491 Christian (2001) for a 6-year-old crop in England (240 cm) and that reported by Ma et al.  
492 (2000) in a sandy loam in Alabama for a 7-year-old crop (330 cm). Evidence of a deep root

493 system for alfalfa was also found in several studies (Campbell et al. 1994; Dardanelli et al.  
494 1997). The maximum rooting depth of 200 cm observed for triticale was consistent with the  
495 highest values reported for winter cereals such as winter wheat (Hoad et al. 2001; King et al.  
496 2003; Zhang et al. 2004). Sorghum had the shallowest root system in our conditions, with  
497 only 128 cm depth. This value was lower than that found by Robertson et al. (1993) for  
498 various grain sorghum cultivars in a sub-tropical environment in Australia (190 cm). Monti  
499 and Zatta (2009) found roots of fibre sorghum in Italy down to 120 cm depth. In our  
500 conditions, sorghum had a short growing period because it was sown after mid-May (May 21  
501 in 2010) due to its susceptibility to low temperatures and this may have limited root  
502 development.

503 Root density has frequently been found to decrease exponentially with depth (Gregory 2006).  
504 This exponential decrease is more or less verified for most crops, but not for alfalfa or  
505 miscanthus (Table 3). The root distribution observed for miscanthus, i.e. a rather low density  
506 in the upper layers with a drastic decrease below 30 cm and a constant and rather high density  
507 in the deeper layers, is consistent with the results of Neukirchen et al. (1999) and Riche and  
508 Christian (2001). However, it differs from the study of Monti and Zatta (2009) who found a  
509 surprisingly very low root density for miscanthus below 90 cm.

510

#### 511 Relationship between root distribution and water capture

512 PWC was correlated to RID, meaning that root density was a limiting factor for extracting  
513 water, at least in deep layers. Indeed, soil-root water transfer occurs mainly in the few  
514 centimetres surrounding the roots, due to limitations in soil and/or root hydraulic conductivity  
515 (Garrigues et al. 2006). However, the shape of the relationship (curvilinear asymptotic)  
516 showed that deep roots with a low density were relatively more efficient for recovering water  
517 than shallower, denser roots. Robertson et al. (1993) found the same type of relationship

518 between water consumption and RLD for grain sorghum with a plateau above an RLD  
519 threshold. Zhang et al. (2004) also reported higher water uptake per unit of root length in  
520 depth than near the soil surface for rain-fed and irrigated winter wheat. When root density  
521 increases, competition between neighbouring roots is enhanced, reducing their relative  
522 efficiency.

523 Water capture equivalent to 15 mm in the 150-210 cm layer was observed for sorghum which  
524 had no roots in this layer. The deepest roots of sorghum might have not been observed due to  
525 spatial variability. It is also possible that upward soil water transfer occurred in these free root  
526 layers due to a hydraulic gradient caused by root uptake in the upper layers. Adding the  $y_0$   
527 parameter (PWC in free root layers) to the model allowed us to take this observation into  
528 account and increase the goodness of fit for annual crops (RMSE was divided by 2.5 on an  
529 average) with no impact for the other crops. We chose to take a common value for  $y_0$  although  
530 it is likely that the upward water transfer depends on soil characteristics and decreases with  
531 depth when the distance to the deepest root increases.

532 The optimized parameters were rather variable between crops. The differences observed for  $a$   
533 (highest PWC achievable by the crop), with lower values for perennial crops, could be partly  
534 explained by differences in soil evaporation between crops. However, the same tendency was  
535 observed when the model was fitted on data excluding the first soil layer. Very different  
536 values obtained for the “resource capture coefficient”  $k$  suggest large differences in water  
537 capture efficiency between crops. Monti and Zatta (2009) also found differences between  
538 crops but their ranking (miscanthus > sorghum > switchgrass) was different from ours  
539 (switchgrass > miscanthus > sorghum). In fact, their data on root density were very different  
540 from ours: low root density of miscanthus in depth compared to switchgrass and sorghum. We  
541 hypothesize that this discrepancy was due to a warmer climate, favourable to sorghum, in

542 Italy and to the presence of a water table close to the soil surface which could penalize root  
543 growth of miscanthus.

544 Differences between crops for  $k$  can result from factors relative to root system or crop  
545 evaporative demand (growing period, morphological factors, etc.). The root system of annual  
546 crops like cereals grows simultaneously to the canopy and achieves its maximal development  
547 at anthesis (King et al. 2003), contrary to perennial crops. Consequently, the deep roots of  
548 annual crops have less time than shallower roots to take up soil water. Robertson et al. (1993)  
549 hypothesized that incomplete water extraction in depth for grain sorghum under severe  
550 drought was due not only to lower root density but also to the lack of time for deeper roots to  
551 extract water between the arrival of roots in the soil layer and crop maturity. An extraction  
552 front travelling down the soil profile with time has been observed for annual crops (Dardanelli  
553 et al. 1997; Dardanelli et al. 2004; Robertson et al. 1993) and is generally attributed to the  
554 growth of the root system. In 2009, the driest year of our experiment, an extraction front  
555 clearly appeared for sorghum: water depletion started approximately late June in the 30-60 cm  
556 layer (one month after sowing), late July in the 60-90 cm layer, mid-August in the 90-120 and  
557 120-150 cm layers and late August for the two deeper layers. This difference in the timing of  
558 water extraction with depth could explain low values of  $k$  and high values of  $a$  observed for  
559 annual crops. Among root characteristics, root spatial arrangement could also explain  
560 differences between crops. For example, the degree of root clustering can significantly change  
561 soil water uptake for a given root density (Beudez et al. 2013). Physiological properties such  
562 as root hydraulic conductivity could also influence the ability of roots to extract soil water  
563 (Nippert et al. 2012).

564

565 **Conclusions**



566 This study provides an original monitoring of soil water utilization by different perennial and  
567 annual energy crops during seven years. As expected, perennial and semi-perennial crops  
568 were characterized by proportional water capture in deep soil layers higher than annual crops.  
569 Conversely, PWC was lower in the upper soil layer for miscanthus and switchgrass than for  
570 the other crops. Semi-perennial crops lead to a greater soil water deficit than the other crops,  
571 due to an important water uptake both in surface and deep layers. Contrary to our initial  
572 hypothesis, perennial C4 crops resulted in similar SWD than annual crops whereas perennials  
573 were more productive and had a deeper root system.

574 Our study also highlights the relationship between water uptake and root distribution of the  
575 crops. PWC was correlated to root density with a curvilinear asymptotic function but its  
576 parameters were crop-dependent. Therefore root density was not the only factor determining  
577 maximal water uptake. Since aboveground biomass was not correlated to SWD, other factors  
578 such as the timing and length of the growing period are likely to affect water use.

579 In the perspective of predicting the effect of bioenergy crops on water drainage, a complete  
580 water balance will have to be made in order to quantify the ratio between evapotranspiration  
581 and drainage for each crop. Our results already indicate that the risk of drainage reduction  
582 compared to annual crops is probably higher with semi-perennial crops like alfalfa than with  
583 perennial C4 crops. The impact of the crops on drainage will also depend on soil and climate  
584 characteristics. Areas with deep soils and low winter rainfall are probably more susceptible to  
585 exhibit large differences in drainage between crops. Further studies are needed to explore this  
586 effect of soil and climate variability. Finally, our dataset will be useful to test and improve  
587 soil-crop models in order to simulate the impact of bioenergy crops on drainage and aquifer  
588 loading under various environmental conditions.

589

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596

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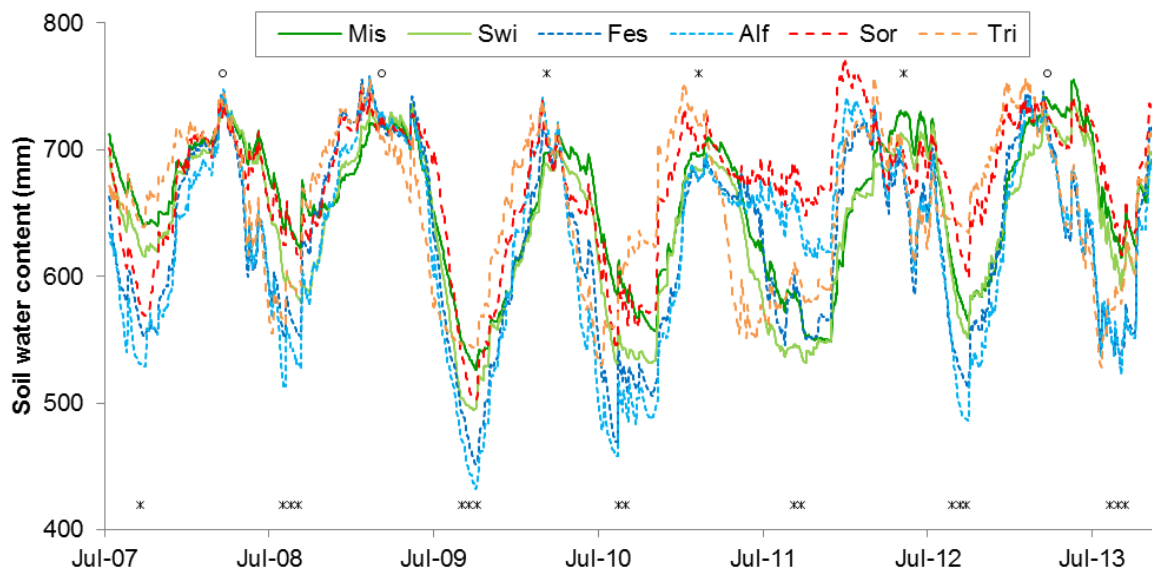
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753 **Fig. 1** Evolution of the soil water content (SWC, 0-210 cm) over time (from July 2007 to  
 754 November 2013) for each crop (Mis = miscanthus; Swi = switchgrass; Fes = fescue; Alf =  
 755 alfalfa; Sor = sorghum; Tri = triticale). For fescue, alfalfa, sorghum and triticale, changes  
 756 between plots were made the first day of March. Asterisks indicate significant differences  
 757 between crops for the highest and lowest SWC of each year (° = NS; \* = p<0.05; \*\* = p<0.01;  
 758 \*\*\* = p<0.001).

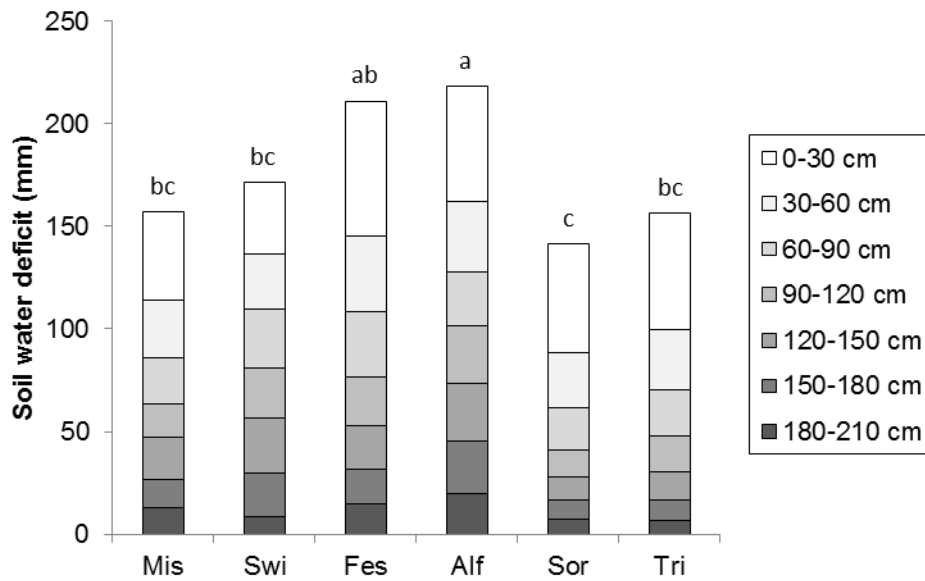


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762 **Fig. 2** Soil water deficit (SWD) calculated for each crop over the period 2007-2013. SWD is  
 763 the mean (over 7 years) of the maximal values of SWD (0-210 cm) encountered during each  
 764 year. Different letters indicate significant differences ( $p < 0.05$ ) between crops. The seven soil  
 765 layers (from 0-30 cm to 180-210 cm) are represented with a grey gradient from white to dark  
 766 grey.

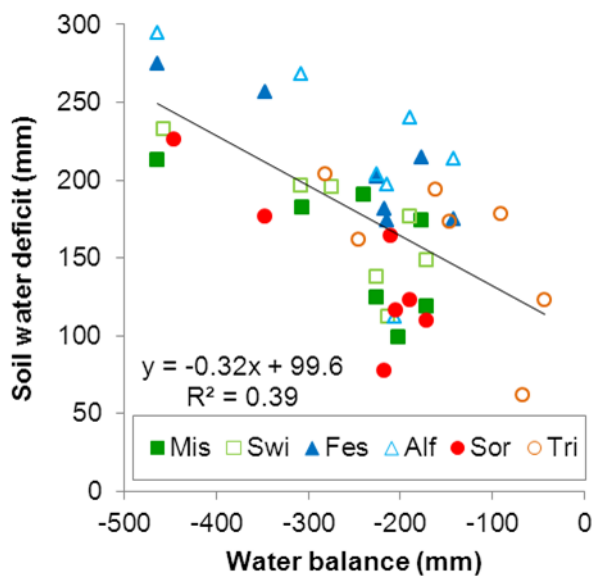


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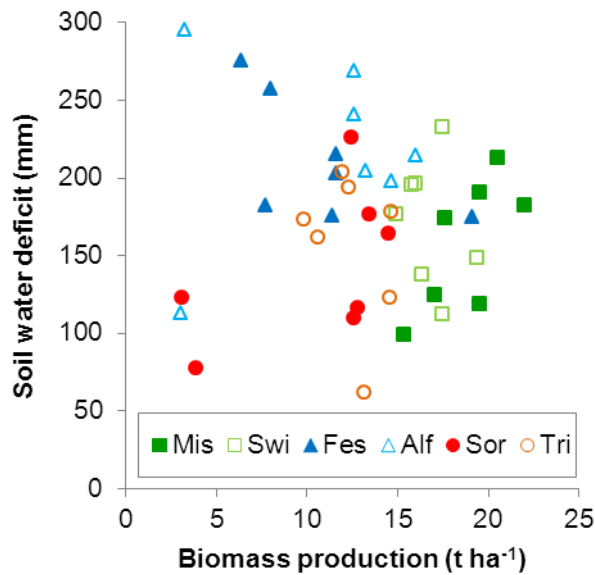
769 **Fig. 3** Relationship between the maximal soil water deficit and the water balance (P+I-PET)

770 observed each year for each crop



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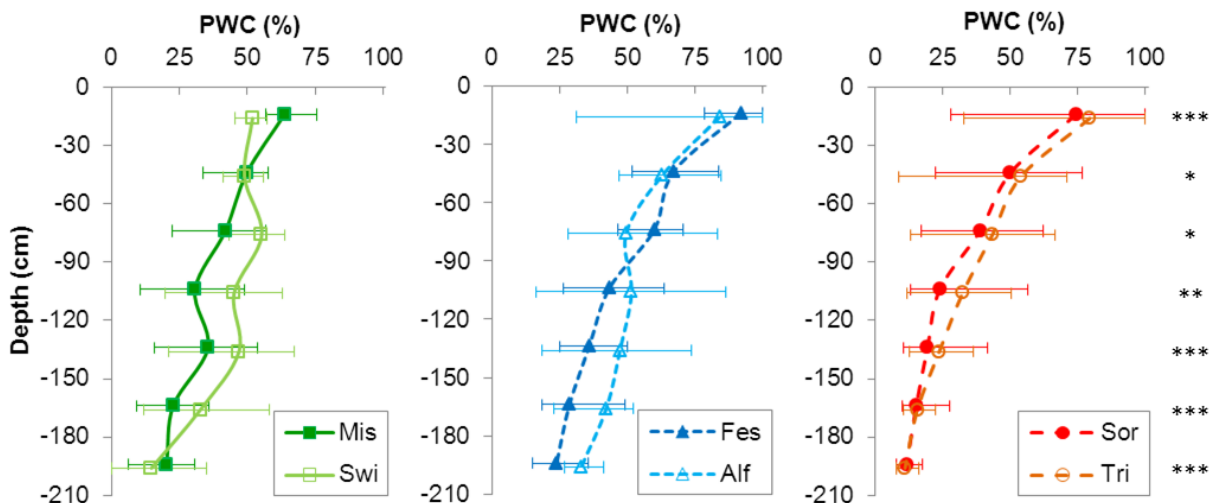
772 **Fig. 4** Relationship between the maximal soil water deficit and the aboveground biomass  
 773 production observed each year for each crop



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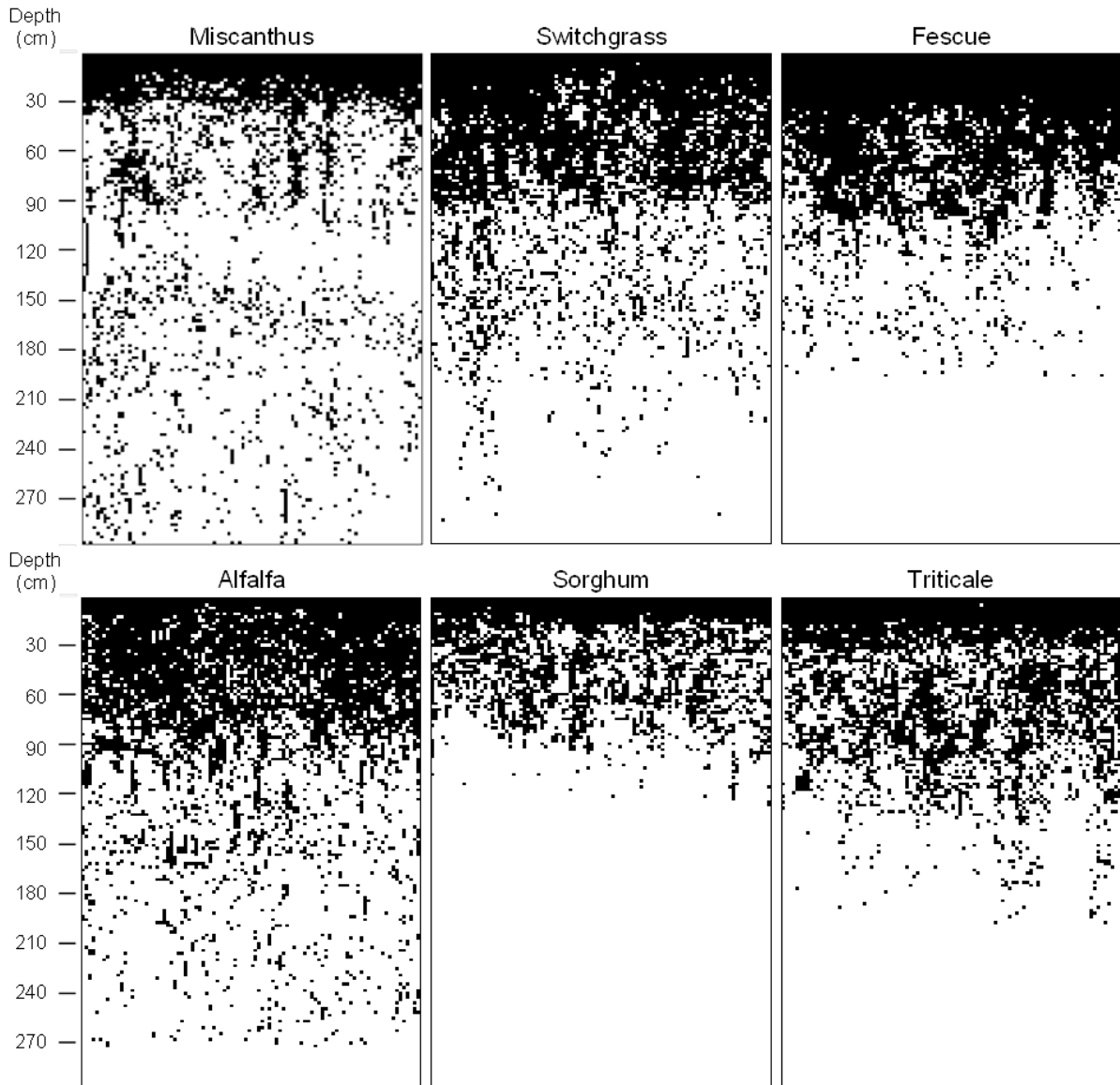
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776 **Fig. 5** Proportional water capture (PWC) versus depth for each crop (Mis = miscanthus; Swi =  
 777 switchgrass; Fes = fescue; Alf = alfalfa; Sor = sorghum; Tri = triticale). PWC is calculated at  
 778 the date of the maximal soil water deficit (mean value over the period 2007-2013). Horizontal  
 779 bars represent the range between the minimal and the maximal values found over the seven-  
 780 year period. Asterisks indicate significant differences between crops in each soil layer (\* =  
 781  $p < 0.05$ ; \*\* =  $p < 0.01$ ; \*\*\* =  $p < 0.001$ ).



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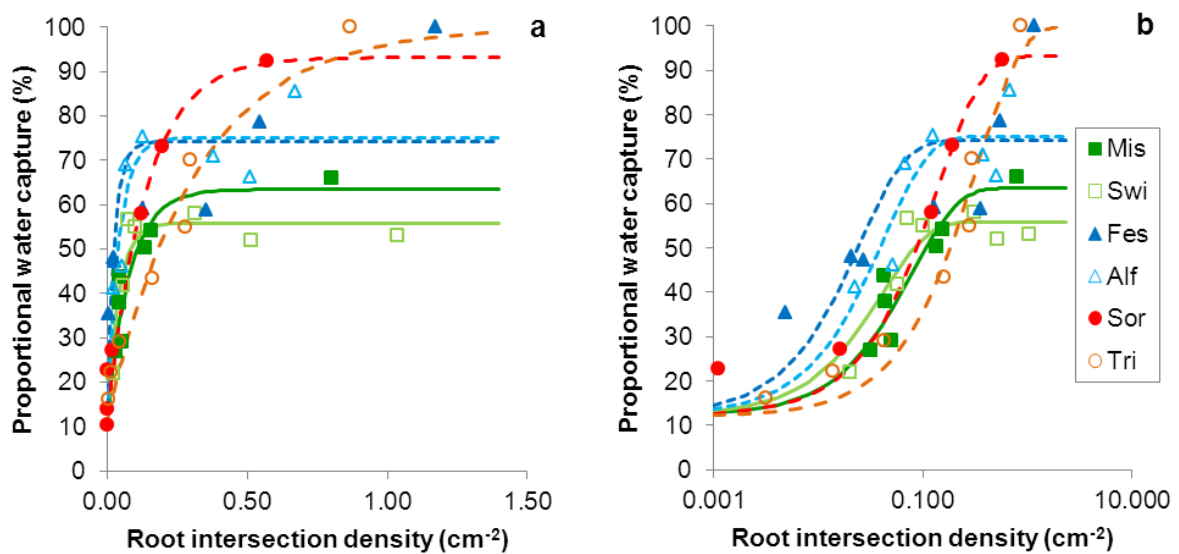
783 **Fig. 6** Spatial distribution of roots observed on the vertical trench wall (180 cm \* 300 cm) for  
784 each crop in 2010. Each black dot represents a grid cell (1.9 \* 1.9 cm) containing at least one  
785 root.



786

787

788 **Fig. 7** Relationship between proportional water capture (PWC) and root intersection density  
 789 (RID) for each crop. PWC was calculated at the date of maximal soil water deficit in 2010: a)  
 790 RID expressed in linear scale; b) RID expressed in logarithmic scale. Symbols are  
 791 experimental data and lines are modelled data. Miscanthus (Mis) is represented by a dark  
 792 continuous line, switchgrass (Swi) by a light continuous line, fescue (Fes) by a dark dotted  
 793 line, alfalfa (Alf) by a light dotted line, sorghum (Sor) by a dark broken line and triticale (Tri)  
 794 by a light broken line.



795

796

797 **Table 1** Meteorological data: P = precipitation (mm), PET = Penman potential  
 798 evapotranspiration (mm) recorded at Estrées-Mons over the period 2007-2013

Year	March-June			July-October			March-October		
	P	PET	P-PET	P	PET	P-PET	P	PET	P-PET
2007	290	364	-73	216	327	-110	507	690	-184
2008	281	350	-69	317	318	-1	598	668	-70
2009	200	341	-142	145	432	-288	344	773	-429
2010	136	374	-239	270	346	-76	406	720	-315
2011	108	328	-219	243	294	-52	351	622	-271
2012	282	294	-13	219	346	-127	501	640	-139
2013	202	293	-91	321	345	-24	523	637	-114
Mean	214	335	-121	247	344	-97	461	679	-217

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800

801 **Table 2** Soil characteristics measured in the experimental plots (mean  $\pm$  standard deviation)

	Soil layers (cm)						
	0-30	30-60	60-90	90-120	120-150	150-180	180-210
Clay (g kg <sup>-1</sup> )	169 $\pm$ 25	227 $\pm$ 33	267 $\pm$ 22	243 $\pm$ 11	222 $\pm$ 12	190 $\pm$ 13	234 $\pm$ 21
Fine silt (g kg <sup>-1</sup> )	320 $\pm$ 17	305 $\pm$ 21	283 $\pm$ 44	277 $\pm$ 20	275 $\pm$ 13	272 $\pm$ 29	305 $\pm$ 10
Coarse silt (g kg <sup>-1</sup> )	459 $\pm$ 16	418 $\pm$ 19	410 $\pm$ 22	440 $\pm$ 16	467 $\pm$ 23	489 $\pm$ 28	404 $\pm$ 5
Fine sand (g kg <sup>-1</sup> )	38 $\pm$ 9	43 $\pm$ 18	37 $\pm$ 21	36 $\pm$ 15	35 $\pm$ 13	46 $\pm$ 13	52 $\pm$ 15
Coarse sand (g kg <sup>-1</sup> )	13 $\pm$ 3	6 $\pm$ 2	2 $\pm$ 1	2 $\pm$ 1	1 $\pm$ 1	1 $\pm$ 1	3 $\pm$ 1
Organic C <sup>a</sup> (g kg <sup>-1</sup> )	9.8 $\pm$ 0.3	6.0 $\pm$ 0.3	3.0 $\pm$ 0.2	2.3 $\pm$ 0.2	2.1 $\pm$ 0.3	1.7 $\pm$ 0.3	2.6 $\pm$ 0.7
pH in water	7.7 $\pm$ 0.2	7.8 $\pm$ 0.2	7.8 $\pm$ 0.1	8.0 $\pm$ 0.1	8.0 $\pm$ 0	8.2 $\pm$ 0.1	8.2 $\pm$ 0.1
CaCO <sub>3</sub> (g kg <sup>-1</sup> )	2 $\pm$ 1	2 $\pm$ 2	1 $\pm$ 1	2 $\pm$ 2	1 $\pm$ 1	1 $\pm$ 2	3 $\pm$ 4
WFC <sup>b</sup> (g kg <sup>-1</sup> )	243 $\pm$ 3	221 $\pm$ 3	219 $\pm$ 3	217 $\pm$ 4	222 $\pm$ 2	228 $\pm$ 6	238 $\pm$ 3
WWP <sup>c</sup> (g kg <sup>-1</sup> )	90 $\pm$ 12	102 $\pm$ 18	107 $\pm$ 11	104 $\pm$ 9	95 $\pm$ 13	89 $\pm$ 6	104 $\pm$ 5
Bulk density (g cm <sup>-3</sup> )	1.47 $\pm$ 0.05	1.55 $\pm$ 0.02	1.57 $\pm$ 0.03	1.58 $\pm$ 0.01	1.55 $\pm$ 0.03	1.49 $\pm$ 0.03	1.51 $\pm$ 0.03

802

803 <sup>a</sup> Anne Method (AFNOR X 31-109)

804 <sup>b</sup> Water content at field capacity (median of field measurements made in March over the  
805 period 2007-2013), corresponding to ca. -20 kPa water potential

806 <sup>c</sup> Water content at permanent wilting point (measured with Richard's pressure plates at -1.5  
807 MPa water potential)

808



809 **Table 3** Root intersection density (mean number of root impacts per cm<sup>2</sup>) measured for each soil layer and crop (mean ± standard deviation).

810 Different letters indicate significant differences (p<0.05) between crops in each soil layer.

Soil layer (cm)	Miscanthus	Switchgrass	Fescue	Alfalfa	Sorghum	Triticale
0-30	0.800 ± 0.159 <i>bc</i>	1.038 ± 0.107 <i>ab</i>	1.173 ± 0.169 <i>a</i>	0.669 ± 0.066 <i>c</i>	0.571 ± 0.056 <i>c</i>	0.867 ± 0.140 <i>abc</i>
30-60	0.155 ± 0.037 <i>b</i>	0.513 ± 0.082 <i>a</i>	0.546 ± 0.009 <i>a</i>	0.510 ± 0.113 <i>a</i>	0.194 ± 0.030 <i>b</i>	0.295 ± 0.084 <i>b</i>
60-90	0.134 ± 0.055 <i>b</i>	0.314 ± 0.018 <i>a</i>	0.352 ± 0.095 <i>a</i>	0.379 ± 0.035 <i>a</i>	0.123 ± 0.013 <i>b</i>	0.278 ± 0.057 <i>a</i>
90-120	0.043 ± 0.016 <i>bc</i>	0.101 ± 0.035 <i>ab</i>	0.127 ± 0.071 <i>ab</i>	0.126 ± 0.042 <i>ab</i>	0.016 ± 0.010 <i>c</i>	0.160 ± 0.058 <i>a</i>
120-150	0.043 ± 0.034 <i>a</i>	0.072 ± 0.039 <i>a</i>	0.027 ± 0.013 <i>a</i>	0.067 ± 0.039 <i>a</i>	0.001 ± 0.001 <i>b</i>	0.042 ± 0.017 <i>a</i>
150-180	0.050 ± 0.006 <i>ab</i>	0.057 ± 0.017 <i>a</i>	0.020 ± 0.012 <i>bc</i>	0.051 ± 0.014 <i>ab</i>	0 ± 0 <i>d</i>	0.014 ± 0.011 <i>c</i>
180-210	0.031 ± 0.022 <i>a</i>	0.020 ± 0.004 <i>ab</i>	0.005 ± 0.002 <i>bc</i>	0.022 ± 0.004 <i>ab</i>	0 ± 0 <i>c</i>	0.003 ± 0.004 <i>c</i>
210-240	0.023 ± 0.010 <i>a</i>	0.010 ± 0.004 <i>b</i>	0 ± 0 <i>c</i>	0.020 ± 0.002 <i>a</i>	0 ± 0 <i>c</i>	0 ± 0 <i>c</i>
240-270	0.020 ± 0.012 <i>a</i>	0.003 ± 0.002 <i>b</i>	0 ± 0 <i>b</i>	0.016 ± 0.009 <i>a</i>	0 ± 0 <i>b</i>	0 ± 0 <i>b</i>
270-300	0.022 ± 0.016 <i>a</i>	0.001 ± 0.001 <i>b</i>	0 ± 0 <i>b</i>	0.001 ± 0.000 <i>b</i>	0 ± 0 <i>b</i>	0 ± 0 <i>b</i>

811

812 **Table 4** Parameter and statistical criterion values obtained for each crop after fitting the  
 813 model describing the relationship between root intersection density and proportional water  
 814 capture (see Eq. 2 in text)

		Miscanthus	Switchgrass	Fescue	Alfalfa	Sorghum	Triticale
<i>a</i>	(%)	63.5	55.9	74.2	75.1	93.2	100.0
<i>k</i>	(cm <sup>2</sup> )	12.6	24.4	39.6	23.9	7.3	3.1
RMSE	(%)	5.4	4.9	13.8	7.3	4.6	5.7

815