1   **Water uptake patterns of pea and barley responded to drought but not to cropping systems**

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13   **Highlights**

14   • Pea and barley shifted to shallower water uptake depths in response to drought.

15   • No niche differentiation was found between pea and barley in a mixture under drought.

16   • No differences on changes in uptake depths by drought were found among cropping systems.

17   • Thus, cropping systems did not compensate drought effects on water uptake patterns.

18 **Abstract**

19 Agricultural production is under threat of water scarcity due to increasingly frequent and severe

20 drought events under climate change. Whether a change in cropping systems can be used as an

21 effective adaptation strategy against drought is still unclear. We investigated how plant water

22 uptake patterns of a field-grown pea-barley (*Pisum sativum* L. and *Hordeum vulgare* L.) mixture, an

23 important fodder intercrop, responded to experimental drought under four cropping systems, i.e.,

24 organic intensive tillage, conventional intensive tillage, conventional no-tillage, and organic

25 reduced tillage. Drought was simulated after crop establishment using rain shelters. Proportional

26 contributions to plant water uptake from different soil layers were estimated based on stable water

27 isotopes using Bayesian mixing models. Pea plants always took up proportionally more water from

28 shallower depths than barley plants. Water uptake patterns of neither species were affected by

29 cropping systems. Both species showed similar responses to the drought simulation and increased

30 their proportional water uptake from shallow soil layer (0-20 cm) in all cropping systems. Our

31 results highlight the impact of drought on plant water uptake patterns for two important crop species

32 and suggest that cropping systems might not be as successful as adaptation strategies against

33 drought as previously thought.

34 **Keywords**: climate change, conservation tillage, organic farming, stable water isotope, water

35 uptake depth

36

1 Introduction

Due to climate change, drought events may occur more frequently and become more severe than at present, and hence water scarcity is worsening in many regions of the world (Schewe *et al.*, 2014; IPCC, 2019). Thus, agriculture is facing increasing pressure to ensure food security under aggravating drought conditions (FAO, 2018; FAO, 2019). Although crop breeding has large potential to enhance agricultural productivity, it should certainly not be seen as the only option. Adaptive crop management to a changing climate is discussed as an additional solution to mitigate yield loss under drought, potentially by sustaining plant growth, enhancing soil water availability, or by promoting mycorrhizal symbiosis (Cochard, 2002; Bot & Benites, 2005; Kundel *et al.*, 2020; Wahdan *et al.*, 2021). Therefore, there is a growing interest in organic farming and conservation tillage (i.e., no tillage or reduced tillage), as these management practices have been shown to be beneficial to soil health and water holding capacity, ecosystem stability, as well as environmental sustainability (e.g., Seitz *et al.*, 2019; Teasdale *et al.*, 2007; Hobbs *et al.*, 2008; Wittwer *et al.*, 2021). However, an evaluation of different cropping systems as a means to support arable crops under drought is still urgently needed (IPCC, 2019).

Understanding plant water relations under drought plays an increasingly important role in promoting sustainable agriculture to secure food production (Penna *et al.*, 2020). Plant water uptake and water use, particularly during critical growing stages, greatly determine physiological processes, survival, and ultimately crop productivity (Boyer & Rao, 1984; Wang *et al.*, 2015). Although many studies reported plant water uptake patterns in response to drought over a broad range of species and environments (e.g., Prechsl *et al.*, 2015; Grossiord *et al.*, 2019; Rasmussen *et al.*, 2020; Ding *et al.*, 2021), only very few focused on arable agriculture (e.g., Zegada-Lizarazu *et al.*, 2006; Borrell *et al.*, 2014; Wu *et al.*, 2018) and none compared arable cropping systems. Moreover, these studies found contrasting responses of crop species to changing environments, illustrating the current gap of knowledge on plant water relations in cropping systems.

62   Plant water uptake mainly depends on soil water availability, root properties and distributions, as

63   well as soil-plant interactions (von Freyberg *et al.*, 2020). Soil water availability depends on soil

64   physical characteristics and local climatic conditions. Root systems, including root distribution and

65   functionality, are affected by soil physical and nutritional conditions as well as plant growth stages

66   and species genetics. Soil-root interactions include hydrotropism, root damage caused by drying

67   soil, and soil water redistribution (Caldwell *et al.*, 1998; Whitmore & Whalley, 2009; Dietrich *et*

68   *al.*, 2017). Furthermore, plant water uptake patterns are highly dynamic and difficult to track. Since

69   the 1960s, stable water isotopes, i.e. oxygen and hydrogen isotopes, have been used in

70   ecohydrology studies (Gonfiantini *et al.*, 1965; Zimmermann *et al.*, 1967), e.g. to assess root water

71   uptake patterns (Rothfuss & Javaux, 2017), to detect foliar water uptake (Berry *et al.*, 2019), as well

72   as to partition evapotranspiration fluxes (Wang *et al.*, 2010). Stable water isotopes have since

73   become a helpful tool to identify plant water uptake sources and quantify source contributions

74   (Dawson & Ehleringer, 1991; Penna *et al.*, 2018). However, studies in agroecosystems have often

75   focussed on grassland species (e.g. Bachmann *et al.*, 2015; Prechsl *et al.*, 2015), much less on crop

76   species as reviewed by Penna *et al.* (2020).

77   Hence, our experimental field study investigated how different cropping systems, namely organic

78   vs. conventional farming with intensive vs. conservation tillage, affect plant water uptake patterns

79   under drought using stable water isotopes. We focused on a pea-barley (*Pisum sativum* L. and

80   *Hordeum vulgare* L.) mixture, an increasingly popular intercrop for fodder production (Gilliland &

81   Johnston, 1992). We aimed at understanding (1) if pea and barley differ in their water uptake

82   patterns when grown in mixture, (2) how drought affects plant water uptake depths, and (3) if

83   cropping systems affect water uptake depths differently.

84   **2   Materials and Methods**

85   **2.1   Research site and experimental setup**

86   The research site is in Rümlang near Zurich (47.26° N, 8.31° E, 489 m a.s.l.), and belongs to the

87   Swiss federal agricultural research station Agroscope. Long-term average annual precipitation at the

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88   site is 994 mm, and mean annual air temperature is 9.7 °C (1988 to 2017; MeteoSwiss, 2020). The

89   soil at the research site is a calcareous Cambisol with 23% clay, 34% silt, and 43% sand, and total

90   soil carbon content of 1.6 to 1.8% (Loaiza Puerta et al., 2018). The plant available soil depth is 50-

91   70 cm, and no groundwater is accessible for plants (Kanton Zürich, 2021). Our study used a sub-set

92   of plots in the Farming Systems and Tillage Experiment which began in 2009 with a six-year crop

93   rotation that is typical for Swiss cropping systems (for details see Wittwer et al., 2017). It combines

94   conventional (C) and organic (O) farming with intensive or soil conservation tillage practices. The

95   conventional systems are managed according to the "Proof of Ecological Performance" (PEP)

96   guidelines of the Swiss Federal Office for Agriculture (Swiss Federal Council, 2021), which allows

97   synthetic fertiliser and pesticide applications. The organic systems were managed following the

98   BioSuisse guidelines, prohibiting the use of mineral fertilisers and synthetic plant protection

99   products. Intensive tillage (IT) with a mouldboard plough to 20 cm depth followed by seedbed

100   preparation with a rotary harrow to 5 cm depth was applied in both conventional (C-IT) and organic

101   systems (O-IT). For conservation tillage, direct sowing and no soil management were implemented

102   in the no tillage conventional plots (C-NT) but glyphosate was sprayed before sowing of the main

103   crops for weed control. A disc or rotary harrow, which superficially disturbed the soil for weed

104   control, was used for reduced tillage in organically managed plots (O-RT) to a maximum depth of

105   10 cm. These four cropping systems were repeated in four blocks following a Latin square design.

106   Cropping system plots had an area of 6 m × 30 m.

107   In 2018, the same pea (*Pisum sativum* L. cv. 'Alvesta') and barley (*Hordeum vulgare* L. cv.

108   'Eunova') mixture was sown in all plots on 26 March and harvested on 12 July (108 days). The

109   mixture was composed of 20% and 80% of the recommended sowing densities of pea (90 seeds/m^2)

110   and barley (350 grains/m^2), respectively. The seeds were sown in a mixture with a standard drill-

111   sowing machine. No fertilisation was applied in any of the treatments because the pea plants were

112   expected to fix dinitrogen from the atmosphere.

113   In order to simulate a future drought scenario (CH2018), portable rain shelters were installed from

114   22 May to 28 June 2018 (37 days) during the 108-day growing season. This resulted in a 34%

115   reduction in precipitation from the drought subplots during the growing season in 2018 (from

116   sowing to harvest; Table 1). No irrigation was applied to the control plots during the (unexpected)

117   naturally dry period in June for logistical and rational reasons, i.e., irrigation is unusual for the

118   region and this crop, and the dry period happened during the ripening phase of the crop. The

119   portable, tunnel-shaped rain shelters (metal frames of 3 m × 5 m base area and 2.1 m height at the

120   highest point) were covered with transparent and ultraviolet light-transmissible plastic foil

121   (Gewächshausfolie UV5, 200 μm, Folitec Agrarfolien-Vertrieb, Germany) and were open at both

122   ends as well as at both sides and had an opening at the top along the full length. This allowed

123   extensive ventilation and prevented temperature build-up (for technical details see Hofer *et al.*,

124   2016). Rain running down the foil was collected in PVC half pipes and directed away from the plots

125   (about 2 m). These drought subplots were established in each cropping system (which were in

126   place since 2009) and located directly next to control subplots which received natural precipitation

127   inputs, resulting in a split-plot layout. A total of 16 experimental plots (four cropping systems ×

128   four replicates) with 32 subplots (16 plots × two water availability treatments) were used in this

129   study. Our experimental design thus compared replicated drought and control sub-plots in parallel

130   (i.e., at the same time), not after each other (i.e., a temporal replication over multiple years), since in

131   crop rotations, the identical crop cannot be grown on the same field for several years due to soil

132   health issues.

133   **2.2   Climatic data and soil water contents**

134   Precipitation and air temperature data (Table 1; Fig. 1) were obtained from a nearby weather

135   station, Zürich/Kloten (KLO, 47.48° N, 8.54° E, 4.6 km north of the research site, MeteoSwiss,

136   2020). Soil water content (SWC) was continuously measured and recorded at 10 and 40 cm depths

137   with two replicates per cropping system (EC-5, Decagon Devices Inc., Pullman, WA, USA; factory-

138 calibrated). Data were averaged at 10 min intervals by data loggers (CR1000 and CR216, Campbell

139 Scientific Ltd., Loughborough, UK), then averaged for daily values.

140 **2.3 Plant and soil water samples for stable isotope analysis**

141 Plant and soil samples were collected on 7 May, 25 June, and 11 July 2018, i.e., before the drought

142 treatment (BT), at the end of the treatment (ET), and after the treatment (AT), respectively. Pea was

143 not sampled AT due to progressed senescence. Root crowns were collected for stable isotope

144 analysis of plant xylem water as this part best reflects the mixture of water sources taken up from

145 the soil in herbaceous plants (Barnard *et al.*, 2006; von Freyberg *et al.*, 2020). Four to six

146 individuals were collected and pooled into one sample per species and subplot. Root crowns were

147 cleaned quickly to remove remaining soil and then immediately sealed in air-tight glass tubes (12-

148 ml exetainer, Labco Ltd., Ceredigion, UK). In parallel to the plant sampling, soil samples were

149 collected close to the sampled plants with a soil auger (1 cm diameter). The soil cores were

150 separated into six depth layers – 0-5, 5-10, 10-20, 20-30, 30-40, and 40-60 cm – and then

151 immediately sealed in glass tubes (18 ml, Schott AG, Mitterteich, Germany). All plant and soil

152 samples for stable water isotope analysis were kept in a cool box in the field and then stored

153 at -18 °C before extraction with cryogenic vacuum distillation (Ehleringer & Osmond, 1989).

154 During the extraction, the samples were kept in an 80 °C water bath, extracted under 10^{-2} MPa for 2

155 h, and the extracted water collected in glass tubes immersed in liquid nitrogen.

156 **2.4 Stable water isotope analyses**

157 The oxygen and hydrogen stable isotope ratios ($\delta^{18}O$ and $\delta^{2}H$) of extracted water samples were

158 analysed by coupling a high-temperature elemental analyser (TC/EA, Finnigan MAT, Bremen,

159 Germany) with an isotope ratio mass spectrometer (IRMS, Delta^{plus}XP, Finnigan MAT, Bremen,

160 Germany) via a ConFlo III interface (Finnigan MAT, see Werner *et al.*, 1999) using the high-

161 temperature carbon reduction method described by Gehre *et al.* (2004). All $\delta^{18}O$ and $\delta^{2}H$ values are

162 expressed relative to the Vienna Standard Mean Ocean Water (VSMOW-SLAP, Craig & Gordon,

163 1965; Gat, 2010) in parts-per-thousand (or "per mil", ‰; eq. 1):

$$\delta^{18}O \text{ or } \delta^2H = \frac{R_{\text{SAMPLE}}}{R_{\text{STANDARD}}} - 1 \qquad (1)$$

164   where R is the isotope ratio of the rare isotope to the abundant isotope ($^{18}O/^{16}O$ or $^2H/^1H$). The long-

165   term precision of the quality-control standard *IsoLab 1* over the last four years was 0.22‰ for d^{18}O

166   and 0.59‰ for d^{2}H.

167   The isotopic composition of precipitation at the global scale shows a linear relationship between the

168    $\delta^{18}O$ and δ^2H of meteoric waters (Global Meteoric Water Line, GMWL; Craig, 1961), described by

169   the regression line in a "dual-isotope" $\delta^{18}O$-δ^2H plot (eq. 2):

$$\text{GMWL: } \delta^2H = 8.2 \times \delta^{18}O + 11.7 \qquad (2)$$

170   Similarly, the Local Meteoric Water Line (LMWL) describes the isotopic composition in rainfall

171   for a specific location (Dansgaard, 1964). We fitted the long-term LMWL (1994 to 2017) with

172   monthly mean data from the closest GNIP station (Global Network of Isotopes in Precipitation,

173   Buchs Suhr, 47.37° N, 8.08° E, 34 km from the research site; IAEA, 2020; eq. 3), while the LMWL

174   of 2018 was fitted with data of precipitation samples collected at the research site (after Prechsl *et*

175   *al.*, 2014; eq. 4) during the growing season and data of 2018 from GNIP Buchs (Fig. S1):

$$\text{long-term LMWL: } \delta^2H = 7.9 \times \delta^{18}O + 6.4 \qquad (3)$$

$$\text{2018 LMWL: } \delta^2H = 8.3 \times \delta^{18}O + 12.7 \qquad (4)$$

176   **2.5   Bayesian mixing model for plant water uptake**

177   Proportional contributions of soil water to plant water uptake (PC) from different depths were

178   estimated using mixing models from the R package 'simmr' (Parnell, 2020) within a Bayesian

179   framework based on code by Parnell *et al.* (2013). The $\delta^{18}O$ or δ^2H signatures of soil water from the

180   six soil layers were used as sources, and plant xylem water was considered the mixture for

181   modelling in each subplot at different sampling times, i.e., BT, ET, and AT. Missing replicates of

182   soil samples due to sampling difficulties (n = 5 in total) were filled with mean values of the other

183   replicates from the same cropping system and treatment to have balanced model inputs. The model

184   outputs consisted of 10 000 possible combinations of PC from different soil depths from four

185   Markov chain Monte Carlo Bayesian models with at least 300 000 iterations, 50 000 burns, and 100

186   times of thinning for each chain. The median of the model outputs on PC (MPC) from each soil

187   depth was calculated for each subplot and used for statistical analysis on plant water uptake depths.

188   Compared to the most frequent value of the model outputs, MPCs of all the sources usually sum up

189   closer to 1. To increase clarity of presentation, PC was grouped into three layers, namely shallow

190   (0-20 cm), middle (20-40 cm), and deep (40-60 cm) soil layers for further analyses. The PC values

191   from shallow and middle layers are the sum of PC from soil depths of 0-5, 5-10, and 10-20 cm, and

192   the sum of PC from soil depths of 20-30 and 30-40 cm, respectively. As $\delta^{18}O$ and $\delta^{2}H$ yielded

193   similar results, only the model outputs of $\delta^{18}O$ are described in detail in this paper.

194   **2.6   Data analyses**

195   For data analyses, the whole growing season was divided into three periods based on the drought

196   treatment, namely before the drought treatment (BT; 26 March to 21 May), the drought treatment

197   period itself (22 May to 28 June) which was sampled directly before the removal of shelters on 28

198   June (termed ET, end of treatment), and after the drought treatment (AT, 29 June to 12 July). All

199   statistical analyses were carried out using R (v3.6.2; R Core Team, 2020). The effects of cropping

200   systems, drought treatment, and species were tested with linear mixed models using the function

201   *lmer()* from the R package 'lmerTest' (Kuznetsova *et al.*, 2017). 'Cropping systems (CS)', 'drought

202   treatment (D)', and 'blocks' were three fixed factors (Dixon, 2016), interactive effects between

203   'CS' and 'D' with 'plots' (accounting for the split-plot design) were considered as random factors.

204   For variables measured on both pea and barley (i.e., stable isotopes of xylem water and MPC for BT

205   and ET), 'plant species', 'CS', 'D', and 'blocks' were tested as fixed factors considering interactive

206   effects among 'plant species', 'CS', and 'D' with 'plots' and 'subplots' as random factors.

207   Diagnostic plots were checked for normality and homoscedasticity of residuals for model

208   assumptions. Differences among cropping systems and between treatments or species were tested

209   by the Tukey HSD (honestly significant difference) test using the function *glht()*, from the R

210   package 'multcomp' ([Hothorn *et al.*, 2008](#)).

211   **3   Results**

212   **3.1   Environmental conditions in drought and control subplots**

213   Air temperatures in 2018 were very high compared to the long-term mean, in particular in May and

214   June, with a daily average air temperature of 15.8 and 18.8 ⁰C, respectively, while the long-term

215   (1988 to 2017) mean air temperatures in these two months were 13.9 and 17.2 ⁰C, respectively

216   (Table 1; Fig. 1). Annual precipitation was relatively low (Table 1). While the precipitation in May

217   2018 (102 mm) was comparable to the long-term mean (1988 to 2017: 105 mm), no precipitation

218   fell between 14 June and 2 July 2018 (naturally dry period), resulting in a below-average

219   precipitation in June (40 mm; long-term mean of 102 mm, Table 1), followed by an even more

220   pronounced drought period in July (Fig. 1). Average daily soil water contents (SWC) in the control

221   subplots ranged from 16% to 29% at 10 cm depth and slightly higher, from 22% to 29%, at 40 cm

222   depth, prior to the rain event on 3 July 2018. After this rain event, SWC increased in all cropping

223   systems at both depths (Fig. 2a, b). Variations in SWC among cropping systems were small,

224   particularly during the naturally dry period in June. SWC in drought subplots of all cropping

225   systems decreased continuously during the 37-day drought treatment (22 May to 28 June 2018),

226   averaging to 13% at 10 cm and to 19% at 40 cm soil depth (Fig. 2 c, d). SWC at 10 cm did not show

227   any pronounced differences among cropping systems, while SWC at 40 cm tended to be slightly

228   higher in cropping systems with conservation tillage (O-RT and C-NT) compared to systems with

229   intensive tillage (O-IT and C-IT; Fig. 2b, d).

230   **3.2   Stable isotopes in soil water and plant xylem water**

231   In the dual-isotope space, stable oxygen and hydrogen isotope ratios of soil and plant xylem waters

232   were strongly related with each other (R^2 = 0.89 and 0.85, respectively; Fig. S1) and generally fell

233   below the local meteoric water line (LMWL) of 2018, representing evaporation. Stable isotope

234   signatures of xylem water were lower than the LMWL but higher than those of soil water,

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235 indicating that xylem water isotope signatures were mixtures of the original source precipitation and

236 the pool of soil water, affected by different degrees of fractionation.

237 The stable water isotope profiles of soil water showed a characteristic pattern at all times, for all

238 cropping systems and both treatments, with most enriched values in the uppermost soil and

239 increasingly depleted values with increasing soil depth (Table S1; Fig. 3 for δ^{18}O; Fig. S2 for δ^2H).

240 The drought treatment showed no significant effects before the treatment (BT) for δ^{18}O nor δ^2H

241 (except for δ^2H at 20-30 cm; Table 2). In contrast, at the end of the drought treatment (ET), soil

242 water δ^{18}O values from 20-60 cm (20-30, 30-40, and 40-60 cm) as well as δ^2H values from all

243 depths were strongly affected by the drought treatment (all $P < 0.05$; Table 2), with more depleted

244 signatures in the drought than in control subplots due to the exclusion of more enriched summer

245 precipitation. Even after the shelters were removed and the treatment had been finished (AT), the

246 drought treatment still significantly affected both δ^{18}O and δ^2H of soil water, albeit only in deeper

247 soil depths (30-40 and 40-60 cm for δ^{18}O and 40-60 cm for δ^2H; all $P < 0.05$; Table 2). Overall,

248 cropping systems did not significantly affect the stable isotopic signatures in soil water at any time

249 (Table 2).

250 Pea xylem water was always significantly more enriched in ^{18}O and ^{2}H compared to barley (all $P <$

251 0.001; Table S2). The δ^{18}O values in xylem water for pea ranged between -8.8‰ and -5.7‰, and

252 significantly lower between -10.1‰ and -5.8‰ for barley (averages per cropping system, treatment,

253 and time; Table 3; Table S2). Similarly, the δ^2H values in xylem water for pea ranged

254 between -65.6‰ and -52.1‰, and significantly lower between -74‰ and -47.1‰ for barley (Table

255 3; Table S2). Overall, isotopic signatures in xylem water became more enriched in ^{18}O and ^{2}H

256 during the growing season for both pea and barley (Fig. 3, Table S2, Fig. S2). On average, the

257 xylem δ^{18}O for pea was -8.5‰ before the treatment (BT) and -7.2‰ at the end of the treatment

258 (ET), compared to -9.8‰ (BT), -8.8‰ (ET), and -6.3‰ after the treatment (AT) for barley. While

259 average δ^2H values for pea were -64.1‰ (BT) and -57.6‰ (ET), δ^2H values averaged -72.2‰

260 (BT), -68.6‰ (ET), and -50.8‰ (AT) for barley (Fig. 3; Table S1; Fig. S2). Since there was a

11

261   strong relationship between $\delta^{18}O$ and δ^2H in xylem water (Fig. S1; $R^2 = 0.85$), our analyses are

262   mainly focused on $\delta^{18}O$ in the text (but see Table 3, Table S2, and Fig. S2 for analyses on δ^2H).

263   For pea, cropping systems did not significantly affect $\delta^{18}O$ nor δ^2H in xylem water at either time

264   (BT and ET; Table S2), while the drought treatment significantly affected the isotopic signatures of

265   ^{18}O only at the end of treatment (ET: $P = 0.022$; no interactions between cropping systems and

266   drought treatment: $P = 0.085$; Table S2). ^{18}O in pea xylem water were significantly more enriched

267   in the drought than in the control subplots (on average, $\delta^{18}O$ of -6.9‰ and -7.7‰, respectively).

268   In contrast to pea, cropping systems significantly affected $\delta^{18}O$ in barley xylem water (ET: $P =$

269   0.035; Table S2). The drought treatment significantly affected the isotope signatures of both ^{18}O

270   and ^2H at the end of treatment (ET: both $P < 0.01$; no interactions between cropping systems and

271   drought treatment; Table S2). However, unlike pea, the xylem water of barley showed significantly

272   lower $\delta^{18}O$ values in drought than in control subplots for all cropping systems (on average, -9.0‰

273   and -8.6‰, respectively), although the difference was small (Table S2). A similar pattern was also

274   observed for δ^2H at the end of treatment (ET), with significantly lower values on average in drought

275   than in control subplots (ET: -71.8‰ and -65.4 ‰, respectively).

276   **3.3   Modelled plant water uptake depths**

277   The outputs of the Bayesian mixing model on the proportional contribution to total plant water

278   uptake (PC) showed highly significantly different behaviours of pea and barley, mirroring some of

279   the differences seen in the xylem water isotopic signatures of these two species (Fig. 4; Fig. 5).

280   Since frequency density distributions provide not only one estimate per soil depth, but a full

281   frequency distribution, the medians were calculated for each soil depth to assist in the analyses

282   (Table S3 for results from $\delta^{18}O$; Table S4 for results from δ^2H). As both stable isotope signatures

283   showed similar results, we here focus on results derived from $\delta^{18}O$ only. In addition, we grouped

284   the uptake depths into shallow (0-20 cm as sum of 0-5, 5-10, and 10-20 cm), middle (20-40 cm as

285   sum of 20-30 and 30-40 cm), and deep (the original 40-60 cm) soil layers (Table 4; Table 5).

286   Overall, both species took up water from the entire soil profile studied (0 to 60 cm soil depth), albeit

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287 with different proportions depending on species, time (i.e., BT, ET, and AT) and treatment (i.e.,

288 control vs. drought; Table 4; Table 5).

289 For pea, soil water contributions to total plant water uptake decreased with increasing soil depth in

290 both control and drought subplots before (BT) and at the end of the treatment (ET) for all cropping

291 systems (Fig. 4). The median of PC values (MPC) differed significantly among shallow (0-20 cm),

292 middle (20-40 cm), and deep (40-60 cm) layers, averaging 47%, 33%, and 16%, respectively, for

293 both treatments and all cropping systems (BT; Table 5; Fig. 4a, c). At ET, pea plants subjected to

294 drought significantly shifted their water uptake to even higher contributions from the shallow layer

295 (67%) and less uptake from middle (22%) and deep (8%) soil layers compared to BT (Table 5; Fig.

296 4d; Table S5). Pea plants in control subplots did not display such a significant shift, but remained

297 with average MPC from shallow, middle, and deep soil layers of 52%, 31%, and 14%, respectively

298 (Table 5; Fig. 4b; Table S5). Cropping systems did not significantly affect MPC before (BT) or at

299 the end of (ET) treatment (also no interactions between cropping systems and drought, Table 5; Fig.

300 4d).

301 In contrast to pea, barley plants showed very different water uptake patterns before the treatment

302 (BT), with significantly lower PC from the shallow soil layer compared to the middle and deep

303 layers. For barley, MPC values averaged 19%, 44%, and 35% for shallow, middle, and deep soil

304 layers, respectively, for both treatments and all cropping systems (Fig. 5a, d). However, at the end

305 of the treatment (ET), barley plants significantly increased the contributions from the shallow layer

306 in drought subplots, similar to pea (Table 5; Fig. 5e; Table S5), resulting in MPC values of 38%,

307 41%, and 18% from shallow, middle, and deep soil layers, respectively. The MPC further shifted

308 after the treatment (AT) to values of 62%, 27%, and 10% from shallow, middle, and deep layers,

309 respectively (Fig. 5f). Also in control subplots, barley plants showed the same significant shift from

310 BT to ET, with MPC values at ET of 35%, 34%, and 29% from shallow, middle, and deep layers,

311 respectively (Table 5; Fig. 5b; Table S5), and from ET to AT with MPC values AT of 59%, 29%,

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312   and 12% from shallow, middle, and deep layers, respectively (Table 5; Fig. 5c; Table S5). Similar

313   to pea, barley water uptake patterns were not significantly affected by cropping systems (Table 5).

314   Overall, MPC values from shallow and deep layers for pea and barley were positively correlated (r

315   = 0.64 and 0.55, respectively; Fig. S3). This means when barley took up more water from the

316   shallow layer, so did pea.

317   Organic as well as reduced/no tillage cropping systems are discussed as adaptation strategies under

318   climate change conditions to ensure arable crop production. Thus, we analysed plant water uptake

319   depths in drought subplots at the end of treatment (ET) more in detail, although cropping systems

320   showed no significant effects on water uptake depths for either species and no interactions occurred

321   between cropping systems and drought treatment (Table 5). Pea plants in both intensive systems (C-

322   IT and O-IT) showed significantly higher (O-IT: 77%) or similar (C-IT: 65%) contributions to total

323   water uptake (as MPC) from the shallow layer (0-20 cm) compared to conservation tillage systems

324   (64% in both C-NT and O-RT; Table 5; Fig. 4d). Conversely, contributions from the middle layer

325   (20-40 cm) for pea at the end of treatment (ET) were only 15% in O-IT compared to 24% in the

326   other three cropping systems (O-RT, C-IT, and C-NT). Differences among cropping systems under

327   drought were even smaller for barley than for pea (Table 5; Fig. 5e). MPC values of barley for

328   uptake from the shallow layer were 47% (C-IT), 39% (O-RT), 31% (O-IT), and 32% (C-NT).

329   Conversely, contributions from the middle layer were the largest in C-NT (47%), followed by O-IT

330   (44%) and O-RT (41%), and lowest in C-IT (34%). The absolute changes in MPC values between

331   before the treatment (BT) and the end of treatment (ET) were not significantly affected by cropping

332   systems for either species, but significantly affected by the drought treatment for pea (for the

333   shallow and middle soil layers; Table S6).

334   **4   Discussion**

335   Root water uptake patterns are often discussed for their important role in plant water relations, but

336   only few studies considered arable crop species (Penna *et al.*, 2020). In addition, most studies on

337   responses of crop root water uptake patterns to drought took place in pots or under controlled

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338 conditions (e.g., Zegada-Lizarazu & Iijima, 2004; Araki & Iijima, 2005), so that information on

339 field conditions is particularly scarce, except maize (Ma & Song, 2016), wheat (Ma & Song, 2018),

340 oilseed rape, and barley in monoculture (Wu *et al.*, 2016). Furthermore, studies comparing the role

341 of different cropping systems for crop water uptake are completely lacking. Here, we showed for

342 the first time that root water uptake patterns of field-grown pea and barley in mixture responded to

343 drought but not to different cropping systems. Subjected to a pronounced drought period (37 d

344 without precipitation), both crop species shifted to relying more on shallow soil layer (0-20 cm) for

345 water uptake. This drought response was independent of the cropping system, i.e., organic vs.

346 conventional farming or intensive vs. conservation tillage.

347 Previous research on root water uptake patterns in crop as well as grassland species showed

348 ambiguous responses to drought. For some species, root water uptake depth was dependent on root

349 distribution during wet periods, but on soil water availability during dry periods (Sprenger *et al.*,

350 2016). Therefore, utilising more water from deep than from shallow soil layer is typically the

351 anticipated drought response, such as barley in monoculture (Wu *et al.*, 2018), maize (Ma & Song,

352 2016), wheat, rice, soybean (Zegada-Lizarazu & Iijima, 2004), or chickpea (Purushothaman *et al.*,

353 2017). However, other studies reported that crop and grassland species do not take up water from

354 deeper depths under drought but even absorb more water from shallow soil layer (e.g., barley in

355 monoculture, maize, pigeon pea, cowpea; Zegada-Lizarazu & Iijima, 2004), or grassland species

356 (Hoekstra *et al.*, 2014; Prechsl *et al.*, 2015; Wu *et al.*, 2016). This is in accordance with our results

357 in which both pea and barley increased their proportional water uptake from shallow layer (0-20

358 cm) at the end of treatment (ET) in the drought subplots. Although soil water contents (SWC) were

359 still higher at 40 cm than at 10 cm at the end of the treatment (ET; Fig. 2c, d), SWC at 40 cm and 10

360 cm depths were both very low. Thus, the whole soil profile showed very low water availability at

361 the end of the treatment (ET), and fine root distributions most likely dominated plant water uptake

362 patterns.

363　　Rooting profiles for legumes with increased proportions of deeper roots under drought, e.g., below

364　　23-30 cm, have been reported (Benjamin & Nielsen, 2006; Purushothaman et al., 2017), although

365　　different responses in root growth to drought were found among different varieties (Kashiwagi et

366　　al., 2006; Kumar et al., 2012; Purushothaman et al., 2017). The architecture of legume root systems

367　　is strongly affected by rhizobia, which typically find better living conditions in terms of oxygen and

368　　nitrogen concentrations higher up in the soil profile than at greater depths (Concha & Doerner,

369　　2020), also in dry soils. Moreover, barley grown under drought conditions has been reported to

370　　develop proportionally more shallow roots (0-20 cm depth) relative to deeper soil depths (Carvalho

371　　et al., 2014). Also, studies on grassland plants (both legume and grass species) found increasing

372　　root biomass production in shallow soil depths (0-15 cm) in response to drought (e.g., Prechsl et al.,

373　　2015). Although we did not investigate root distributions for either crop species, they most likely

374　　followed such evolutionary strategies as well during our rather strong, 37-day drought treatment, in

375　　addition to recent crop breeding efforts leading to less deep root systems in general (Canadell et al.,

376　　1996; Thorup-Kristensen et al., 2020). Moreover, shifting to shallower water uptake depths during

377　　drought might actually be beneficial for nutrient acquisition (Querejeta et al., 2021), since not only

378　　concentrations of soil water and atmospheric N_2 are higher in the top soil than in the deeper soil, but

379　　also litter inputs for N mineralisation. Thus, besides the low soil moisture within the entire soil

380　　profile, acclimation of the root systems most likely also contributed to the shift towards shallower

381　　water uptake depths under drought for both pea and barley in this study.

382　　The year 2018 was characterised by low precipitation during our experimental period, when a

383　　naturally dry period occurred at the end of our pronounced drought treatment in June (which

384　　excluded 34% of the precipitation during the growing season; Table 1). Our treatment compared

385　　well with the climate scenarios available for Switzerland, with a 25% reduction of precipitation in

386　　2060, and up to 40% by the end of the century; and an increase of the longest rain-free summer

387　　period (June, July, August) from currently 11 days to 20 days (CH2018). The dry period in June

388　　affected pea and barley plants in our control subplots differently (Fig. 6a, b). While pea did not shift

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389   its water uptake pattern (Fig. 6a; Table S5), barley grown in the control subplots reacted very

390   similar to the natural dry period (before the ET sampling, 14 to 25 June; Fig. 2) as barley subjected

391   to our drought treatment, namely with a clear shift from deep (40-60 cm) to shallow (0-20 cm) soil

392   layer (Fig. 6b, d; Table S5). However, barley still relied more on water uptake from the deep soil

393   layer during this naturally dry period in the control subplots than under the experimental drought (P

394    $= 0.017$; Table 5). Hence, these different reactions of the two species to the dry period clearly

395   indicated that barley was more susceptible than pea even to a mild water stress. This observation is

396   fully in line with measurements of stem hydraulic traits (i.e., loss of xylem conductance) from the

397   same experiment (Sun *et al.*, 2021). Barley plants lost xylem conductance much earlier than pea

398   plants when xylem water potentials decreased. In addition, legumes like pea can maintain low

399   stomatal conductance to avoid water stress without compromising photosynthesis when growing

400   under conditions with limiting water supply, due to their high foliar N concentrations (Adams *et al.*,

401   2018). This adds to the hydraulic trait benefits of pea and explains why pea was less affected by the

402   natural dry period. Nevertheless, as shown in our study, if severities and frequencies of droughts

403   increase in the future, one can expect negative consequences not only on the performance of barley,

404   but also of pea (Martin & Jamieson, 1996).

405   Moreover, the two species growing together in the pea-barley mixture showed distinct niches for

406   root water uptake before drought, with pea relying more on water from shallow (0-20 cm) and

407   barley from deep (40-60 cm) soil layers, in accordance with resource partitioning in the absence of

408   water limitation as observed in intercrops, e.g., pearl millet and cowpea (Zegada-Lizarazu *et al.*,

409   2006) and in mixed-species grasslands (e.g., Hoekstra *et al.*, 2014). However, the niches became

410   more similar under drought conditions, contradicting ecological theory which postulates more

411   pronounced niche differentiation and less niche overlap under stressful conditions, such as during a

412   drought (see Nippert & Knapp, 2007; Silvertown *et al.*, 2015; Guderle *et al.*, 2018). However, our

413   results were in line with results from biodiversity studies in temperate grasslands (Bachmann *et al.*,

414   2015; Barry *et al.*, 2020; Hoekstra *et al.*, 2014) which also did not show niche differentiation in

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response to increased competition or drought. Thus, further detailed knowledge on the dynamics of

intercrop water uptake patterns is needed to solve this contradiction and to decrease the uncertainty

for arable crop production now and under future climate conditions.

As global agriculture has already been considerably compromised by and become increasingly

sensitive to climate change (Ortiz-Bobea et al., 2021), farming practices such as organic

management and conservation tillage are being discussed widely. They have been shown to

improve general soil conditions compared to conventional management and intensive tillage,

particularly under drought (Bot & Benites, 2005; Gomiero et al., 2011; Choudhary et al., 2016). For

instance, organic management and conservation tillage can increase soil water holding capacity,

therefore providing higher water availability than conventional management and intensive tillage

(e.g., Colombi et al., 2019; Kundel et al., 2020). In this study, the systems with conservation tillage

(C-NT and O-RT) indeed showed slightly higher SWC than systems with intensive tillage (C-IT

and O-IT) at 40 cm (Fig. 2d). However, this did not result in any benefit for root water uptake

patterns of pea and barley against drought. Water uptake of both species shifted to the shallow layer

(0-20 cm) in all cropping systems under drought, without cropping system effects or interactive

effects between cropping systems and drought treatment. Thus, any further changes in soil physical

characteristics due to the drought treatment among cropping systems did not affect the observed

root water uptake patterns. The relatively short period that annual crop species are growing under

these conditions might limit the potential benefits from improved soil conditions present in those

systems (e.g., Dennert et al., 2018; Loaiza Puerta et al., 2018; Schluter et al., 2018). Although it

remains to be seen if the observed behaviour of a pea-barley mixture also holds true for other crop

species, our results clearly challenge the potential of cropping management under temperate climate

as a tool to adapt arable agriculture to climate change.

5   Conclusions

Water uptake patterns of pea and barley both shifted under drought in all cropping systems and both

species relied more on water from the shallow soil layer (0-20 cm) than on water from deeper in the

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soil profile. This was also the case for organic and reduced/no tillage cropping systems, which are often discussed as beneficial for crop performance, particular under water-limited conditions, and are thus suggested as adaptive cropping management practices under a future climate. However, in this study, we showed for the first time that cropping systems could not counteract the effects of severe drought on plant water uptake patterns for pea and barley grown in mixture. It remains to be seen if this observation also holds true for other, major crops grown under water-limited conditions.

Author Contribution

NB, AKG, RW, and MH designed the study; QS analysed the data; QS, AKG, and NB wrote the first drafts of the manuscript; all authors discussed the results, revised, and agreed on the final version of the manuscript.

Conflict of Interest

None declared.

Supporting Information

Additional supporting information can be found in the online version of this article.

465   Table S1 Stable water isotope values ($\delta^{18}O$ and δ^2H, ‰) of soil in control and drought subplots

466   under different cropping systems.

467   Table S2 Effects of cropping systems, drought treatment and the interaction on stable isotope data

468   ($\delta^{18}O$ and δ^2H, ‰) of pea and barley as well as mean $\pm$ 1 SE for each species in control and drought

469   subplots under different cropping systems.

470   Table S3 Effects of cropping systems, drought treatment and the interaction on the median

471   proportional contributions from different soil depths to water uptake of pea and barley as well as

472   mean $\pm$ 1 SE of MPC using $\delta^{18}O$ data.

473   Table S4 Effects of cropping systems, drought treatment and the interaction on the median

474   proportional contributions from different soil depths to water uptake of pea and barley as well as

475   mean $\pm$ 1 SE MPC using δ^2H data.

476   Table S5 Effects of cropping systems, sampling times and the interaction on the proportional

477   contributions from different soil depths to water uptake of pea and barley simulated from $\delta^{18}O$ data

478   in control and drought subplots.

479   Table S6 Effects of cropping systems, drought treatment and the interaction on absolute changes in

480   median proportional contributions to plant water uptake of pea and barley.

481   Fig. S1 Dual isotope plot of soil and plant samples from control and drought subplots.

482   Fig. S2 δ^2H values of soil water from different depths and plant xylem water in each cropping

483   system in 2018.

484   Fig. S3 Relationships of median proportional contributions to plant water uptake from the shallow

485   and deep soil layers of pea vs. barley.

486   **Data Availability Statement**

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688

24

689 Table 1 Precipitation and air temperature data from a nearby weather station, Zürich/Kloten (KLO,

690 47.48° N, 8.54° E, 4.6 km north of the research site, MeteoSwiss, 2020) as well as dates for the

691 growing season (from sowing to harvest) and treatment periods in 2018.

	Date	Total precipitation (mm)	Mean air temperature (°C)
Long-term annual (1988-2017)	1 January to 31 December	994	9.7
Annual (2018)	1 January to 31 December	856	11.2
Long-term May (1988-2017)	1 to 31 May	105	13.9
May 2018	1 to 31 May	102	15.8
Long-term June (1988-2017)	1 to 30 June	102	17.2
June 2018	1 to 30 June	40	18.8
Growing season 2018	26 March to 12 July	231	15.7
Before drought treatment	26 March to 21 May	108	12.7
During drought treatment	22 May to 28 June	79 (34% of the growing season)	18.7
After drought treatment	29 June to 12 July	44	20.0

692

693   Table 2 Effects of cropping systems (CS, df = 3), drought treatment (D, df = 1) and the interaction

694   (CS × D, df = 3) on stable water isotopes ($\delta^{18}O$ and δ^2H) in different soil depths before the drought

695   treatment on 7 May, at the end of treatment on 25 June, and after the treatment on 11 July (in 2018

696   tested by linear mixed models (*P* values are given).

Isotope	Depth (cm)	CS	D	CS × D	Blocks
			Before drought treatment		
$\delta^{18}O$	0-5	0.580	0.555	0.458	0.788
	5-10	0.119	0.276	0.073	0.367
	10-20	0.489	0.836	0.516	0.459
	20-30	0.201	0.164	0.128	0.069
	30-40	0.135	0.437	0.882	0.311
	40-60	0.960	0.898	0.845	0.404
δ^2H	0-5	0.831	0.120	0.423	0.982
	5-10	0.158	0.118	0.056	0.516
	10-20	0.467	0.416	0.574	0.571
	20-30	0.105	**0.026**	0.064	0.181
	30-40	0.089	0.125	0.959	0.308
	40-60	0.560	0.291	0.853	0.436
			End of drought treatment		
$\delta^{18}O$	0-5	0.316	0.835	0.253	0.367
	5-10	0.189	0.247	0.766	0.168
	10-20	0.080	0.603	0.920	0.673
	20-30	0.898	**<0.001**	0.852	0.940
	30-40	0.437	**<0.001**	0.651	0.954
	40-60	0.073	**0.008**	0.616	0.594
δ^2H	0-5	0.295	**<0.001**	0.168	0.479
	5-10	0.330	**0.005**	0.859	0.215
	10-20	0.091	**0.029**	0.700	0.659
	20-30	0.889	**<0.001**	0.863	0.820
	30-40	0.388	**<0.001**	0.551	0.970
	40-60	0.136	**0.006**	0.469	0.809
			After drought treatment		
$\delta^{18}O$	0-5	0.393	0.059	0.848	0.291
	5-10	0.730	0.672	0.111	**0.031**
	10-20	0.538	0.612	0.734	0.993
	20-30	0.933	0.136	0.936	0.944
	30-40	0.881	**0.048**	0.979	0.772
	40-60	0.751	**0.001**	0.560	0.380
δ^2H	0-5	0.776	0.056	0.667	0.421
	5-10	0.117	0.958	0.649	0.636
	10-20	0.228	0.887	0.926	0.815
	20-30	0.710	0.104	0.888	0.705
	30-40	0.877	0.050	0.919	0.699
	40-60	0.841	**<0.001**	0.493	0.484

697   Significant differences are shown in bold (*P* < 0.05).

698 Table 3 Effects of species (df = 1), cropping systems (CS, df = 3), drought treatment (D, df = 1) and

699 the interaction (species × CS, df = 3; species × D, df = 1; CS × D, df = 3; species x CS × D, df = 3)

700 on stable water isotopes (δ^2H and δ^{18}O) of pea and barley before the drought treatment on 7 May

701 and at the end of treatment on 25 June in 2018 tested by linear mixed models (*P* values are given).

Factor	Before drought treatment		End of drought treatment	
	δ^{18}O	δ^2H	δ^{18}O	δ^2H
Species	**<0.001**	**<0.001**	**<0.001**	**<0.001**
CS	0.251	0.382	**0.038**	0.055
D	0.106	**<0.001**	0.143	**0.001**
Species × CS	0.184	**0.023**	0.312	0.348
Species × D	0.796	0.486	**0.004**	**0.016**
CS × D	0.190	0.117	0.051	0.081
Species × CS × D	0.290	**0.045**	0.120	0.070
Blocks	0.485	0.599	**0.004**	0.162

702

703 Significant differences are shown in bold (*P* < 0.05).

27

704 Table 4 Effects of species (df = 1), cropping systems (CS, df = 3), drought treatment (D, df = 1) and

705 the interaction (species × CS, df = 3; species × D, df = 1; CS × D, df = 3; species × CS × D, df = 3)

706 on the median proportional contributions from different soil depths to water uptake (MPC) of pea

707 and barley before the drought treatment on 7 May and the end of treatment on 25 June in 2018

708 tested by linear mixed models (P values are given).

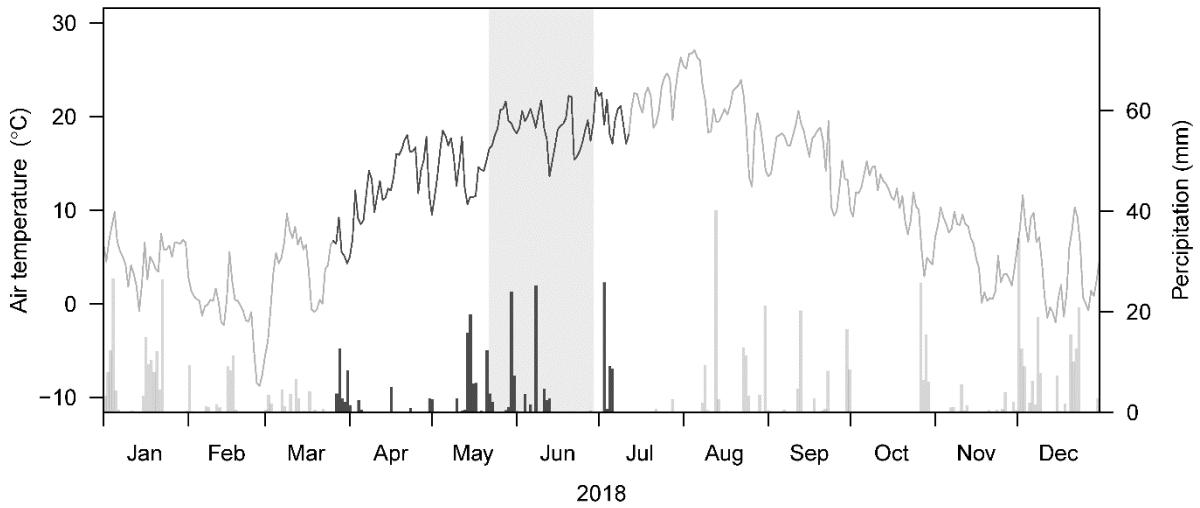| Factor	Before drought treatment			End of drought treatment		
	0-20 cm	20-40 cm	40-60 cm	0-20 cm	20-40 cm	40-60 cm
Species	**<0.001**	**0.036**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
CS	0.506	0.555	0.992	0.374	0.440	0.252
D	0.849	0.775	0.629	**0.003**	0.546	**0.004**
Species × CS	0.255	0.865	0.702	0.303	0.799	0.180
Species × D	0.424	0.619	0.336	**0.009**	**0.001**	0.359
CS × D	0.454	0.293	0.098	0.278	0.811	0.141
Species × CS × D	0.404	0.064	0.079	0.201	0.315	0.495
Blocks	0.360	0.667	0.534	**0.008**	0.115	**0.016**

709

710 MPC was derived from 10 000 simulations by mixing models using $\delta^{18}O$ data. Proportional

711 contribution from 0-20 cm is the sum from 0-5, 5-10, and 10-20 cm, and 20-40 cm is the sum from

712 20-30 and 30-40 cm. Significant differences are shown in bold ($P < 0.05$).

Table 5 Median proportional contributions (MPC) from different soil depths to water uptake of pea and barley before the drought treatment on 7 May, at the end of treatment on 25 June, and after the drought treatment on 11 July in 2018 (left) as well as effects of cropping systems (CS, df = 3), drought treatment (D, df = 1) and the interaction (CS × D, df = 3) on MPC tested by linear mixed models. Means ± 1 SE (MPC) and P values are given.

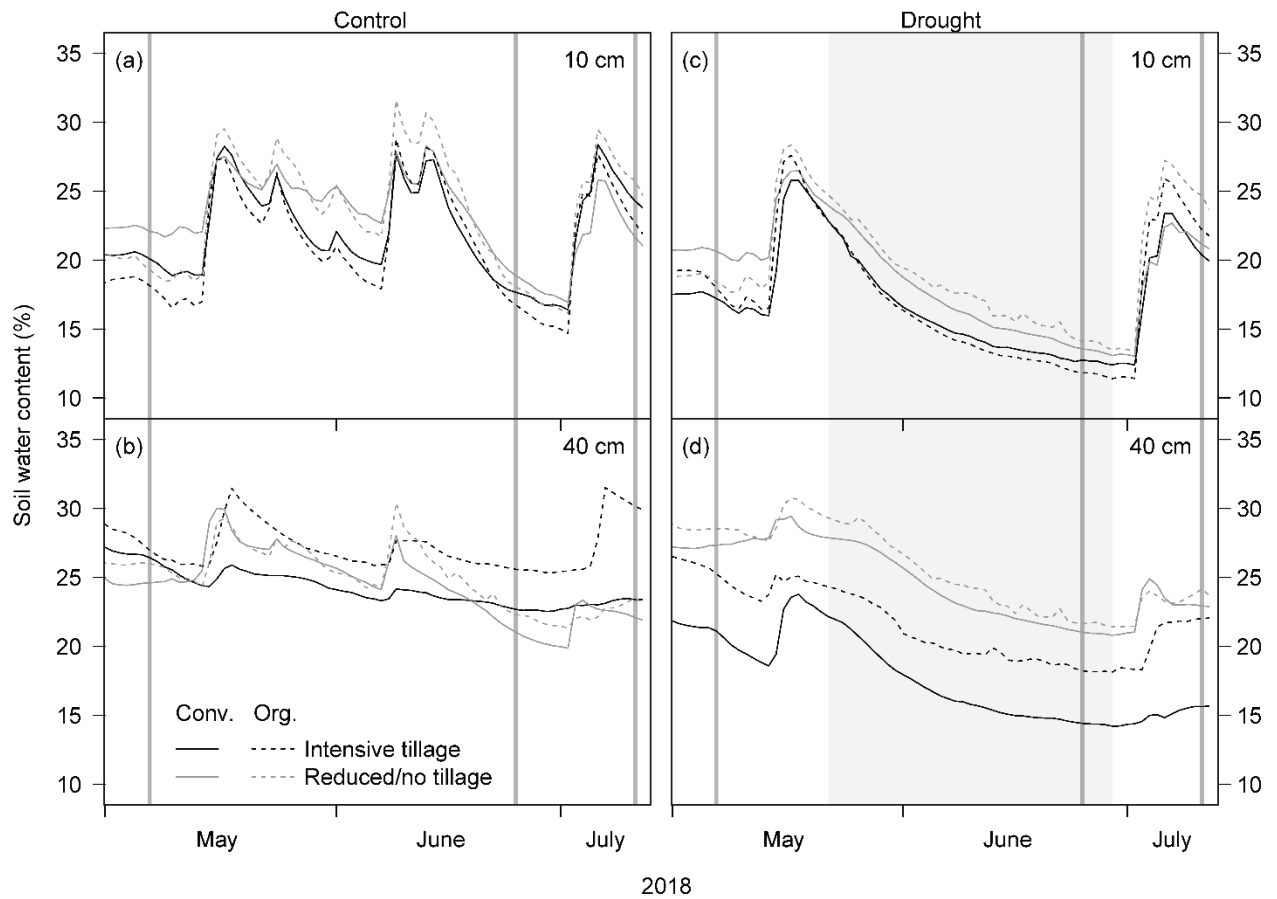| Species | Depth (cm) | MPC | | | | | | | | P value from linear mixed models | | | |
		Control				Drought							
		C-IT	C-NT	O-IT	O-RT	C-IT	C-NT	O-IT	O-RT	CS	D	CS × D	Blocks
						Before drought treatment							
Pea	0-20	45±8	46±9	50±6	48±5	47±9AB	54±7B	34±9A	50±4AB	0.823	0.818	0.313	0.780
	20-40	37±6	29±3	32±4	36±3	35±7	27±3	36±8	33±3	0.557	0.834	0.913	0.656
	40-60	16±3	20±8	12±2	13±2	14±3	14±4	26±11	13±1	0.746	0.665	0.216	0.545
Barley	0-20	10±3	26±12	17±9	14±5	25±11AB	30±11B	11±7A	14±6AB	0.302	0.475	0.535	0.058
	20-40	41±16ab	39±9ab	65±16b	22±11a	55±15AB	29±10A	37±21AB	63±13B	0.736	0.707	0.156	0.785
	40-60	49±19ab	31±12ab	15±7a	63±17b	18±6	38±19	49±24	20±8	0.940	0.467	0.100	0.634
						End of drought treatment							
Pea	0-20	63±6b	46±13a	48±9ab	51±4ab	65±4AB	64±14A	77±12B	64±7A	0.416	**0.001**	0.170	**0.01**
	20-40	27±5a	36±9b	31±3ab	31±1ab	23±2AB	24±9B	15±8A	24±5B	0.416	**0.003**	0.703	**0.021**
	40-60	8±1a	16±4ab	18±6b	14±5ab	9±1AB	10±4B	6±3A	8±1AB	0.398	**0.008**	0.272	**0.027**
Barley	0-20	43±2	38±11	28±6	30±8	47±7B	32±5A	31±9AB	39±7AB	0.214	0.459	0.488	**0.034**
	20-40	39±3	36±4	32±8	29±6	34±4A	47±4B	44±5AB	41±4AB	0.669	0.065	0.339	0.963
	40-60	15±1a	23±9ab	40±13b	38±13b	15±2	19±3	24±8	17±3	0.207	**0.017**	0.213	**0.028**
						After drought treatment							
Barley	0-20	61±9	62±8	56±8	56±8	64±13	55±13	71±8	57±5	0.696	0.546	0.436	**0.001**
	20-40	28±6	25±5	30±5	31±5	25±9	31±9	20±6	31±4	0.664	0.604	0.508	**0.004**
	40-60	10±2	11±3	13±4	12±3	11±4	13±4	7±2	10±1	0.852	0.401	0.225	**<0.001**

MPC was derived from 10 000 simulations by mixing models using $\delta^{18}O$ data. Pea plants were already senesced in early July therefore no stable water isotope data are available after the treatment. Proportional contribution from 0-20 cm is the sum from 0-5, 5-10, and 10-20 cm, and 20-40 cm is the sum from 20-30 and 30-40 cm. Mean ± 1 SE for MPC (%) are given for different cropping systems (C-IT for Conventional intensive tillage, C-NT for Conventional no tillage, O-IT for Organic intensive tillage, and O-RT for Organic reduced tillage). Different small and capital letters indicate significant differences among cropping systems in control and drought subplots, respectively, tested with Tukey HSD (honestly significant difference, $P < 0.05$). Significant effects tested with linear mixed models are shown in bold ($P < 0.05$).
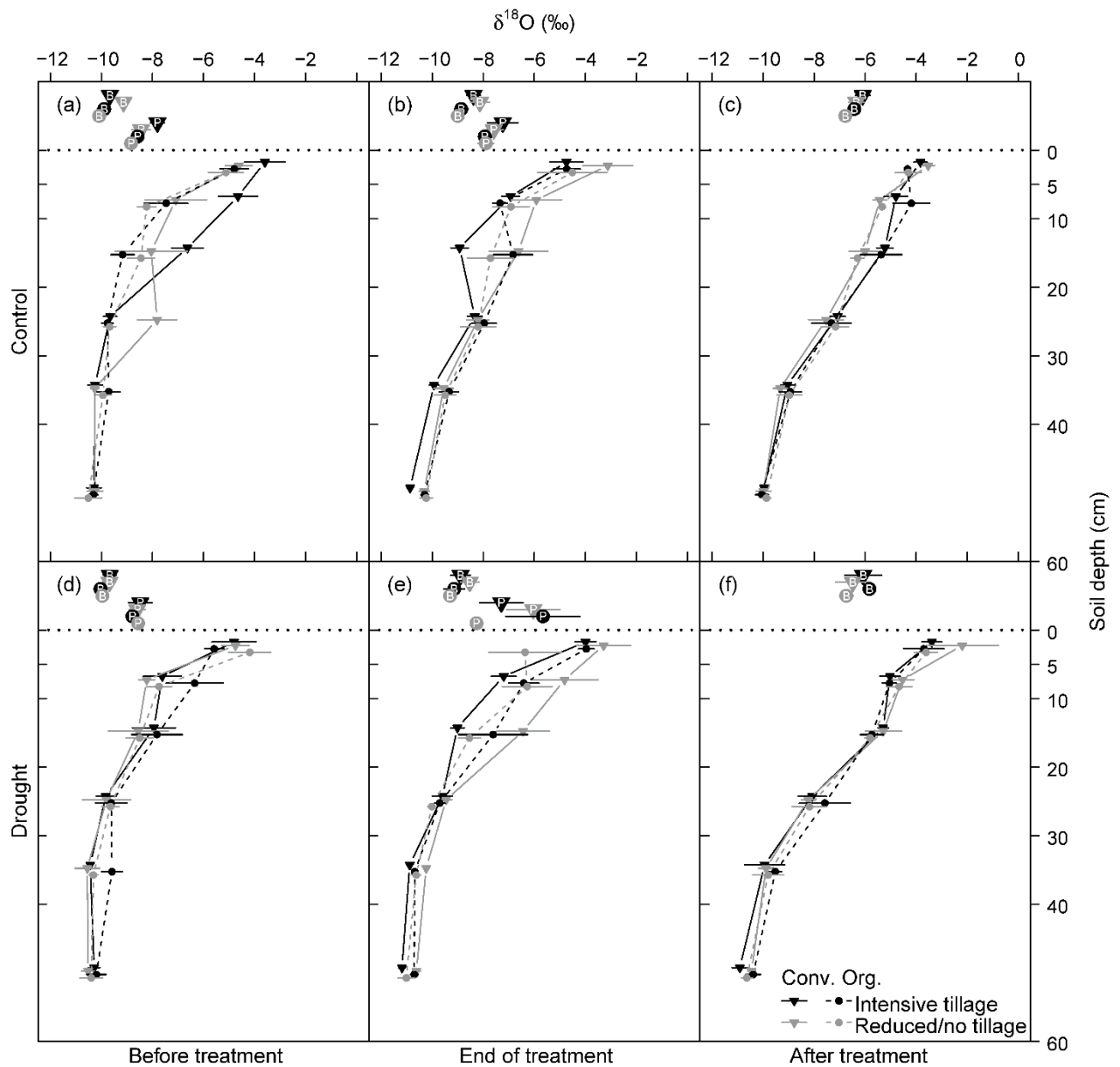
728

729 Fig. 1 Daily air temperature and precipitation in 2018. Dark line segments and bars depict the crop

730 growing season from 26 March to 12 July 2018. The shaded area indicates the drought treatment

731 from 22 May to 28 June 2018. Data from the MeteoSwiss station Zürich/Kloten (KLO, 47.48° N,

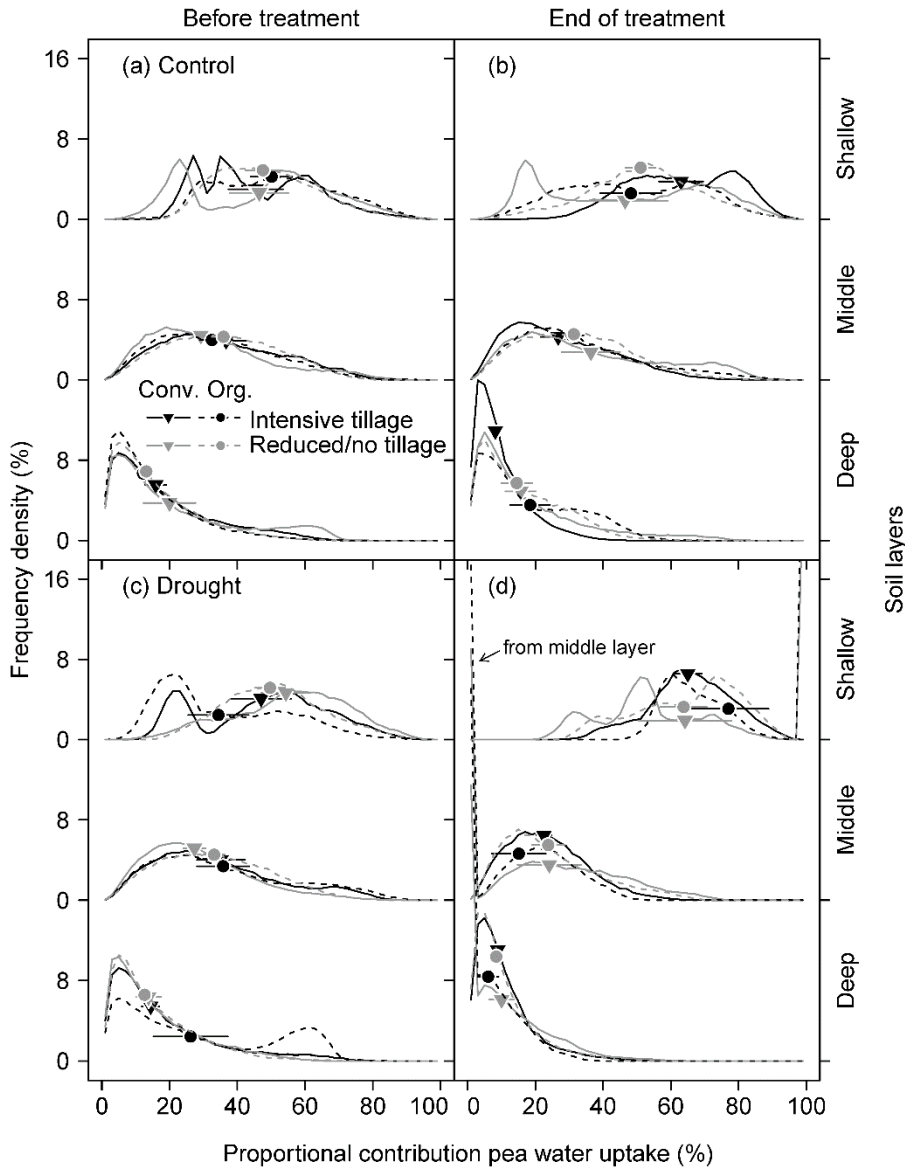732 8.54° E, 4.6 km north of the research site, MeteoSwiss, 2020) are given.

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734

735   Fig. 2 Daily mean soil water contents at 10 and 40 cm depth in (a, b) control and (c, d) drought

736   subplots under different cropping systems (n = 2 each; Conv. for conventional, Org. for organic).

737   Vertical lines indicate sampling dates for stable water isotopes on 7 May, 25 June, and 11 July

738   2018. Shaded areas in (c) and (d) represent the drought treatment period from 22 May to 28 June

739   2018.

Fig. 3 $\delta^{18}O$ values of soil water from different depths and plant xylem water in each cropping system (a, d) before the drought treatment on 7 May, (b, e) at the end of the drought treatment on 25 June, and (c, f) after treatment on 11 July in 2018 (Conv. for conventional, Org. for organic). Horizontal dotted lines separate isotopic composition of soil and plant samples (P for pea, B for barley). Pea plants were already senesced in early July, therefore no stable water isotope data are available after the drought treatment. Means and 1 SE (horizontal bars) are given for each cropping system (n = 3-4).
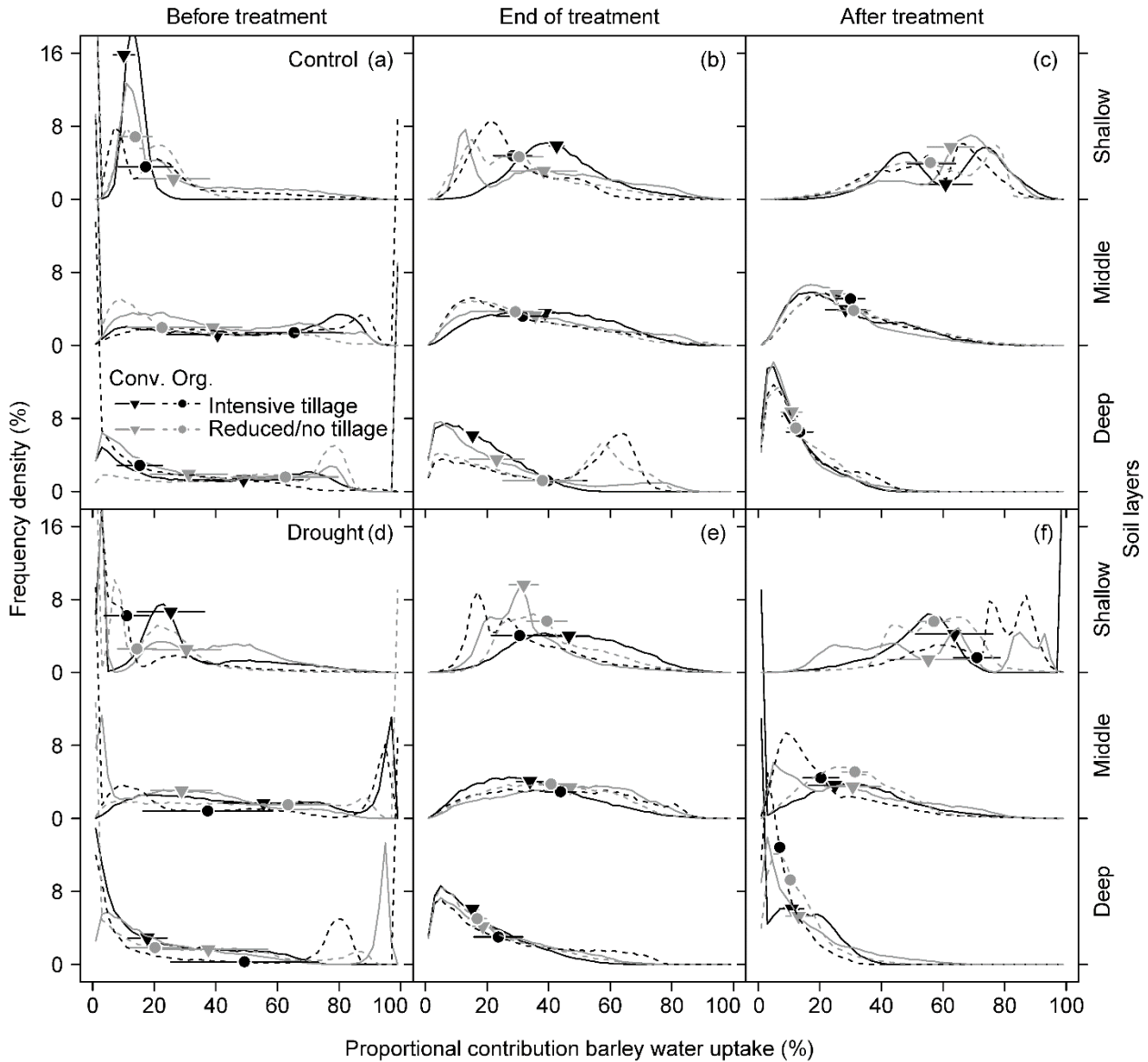
748

749   Fig. 4 Frequency density distribution of model outputs on the proportional contribution of soil water

750   to pea water uptake from shallow (0-20 cm, sum of 0-5, 5-10, and 10-20 cm), middle (20-40 cm,

751   sum of 20-30 and 30-40 cm), and deep (40-60 cm) soil layers under different cropping systems (a,

752   b) before the drought treatment on 7 May and (c, d) at the end of treatment on 25 June in 2018.

753   Frequency density was derived from 10 000 simulations at 2% increment of mixing models using

754    $\delta^{18}O$ for each subplot (Conv. for conventional, Org. for organic). Data were pooled for all subplots

755   in each cropping system. Symbols on the curves indicate the median of the model outputs for each

756   soil layer. Means and 1 SE (horizontal bars) of each cropping system are given (n = 3-4).
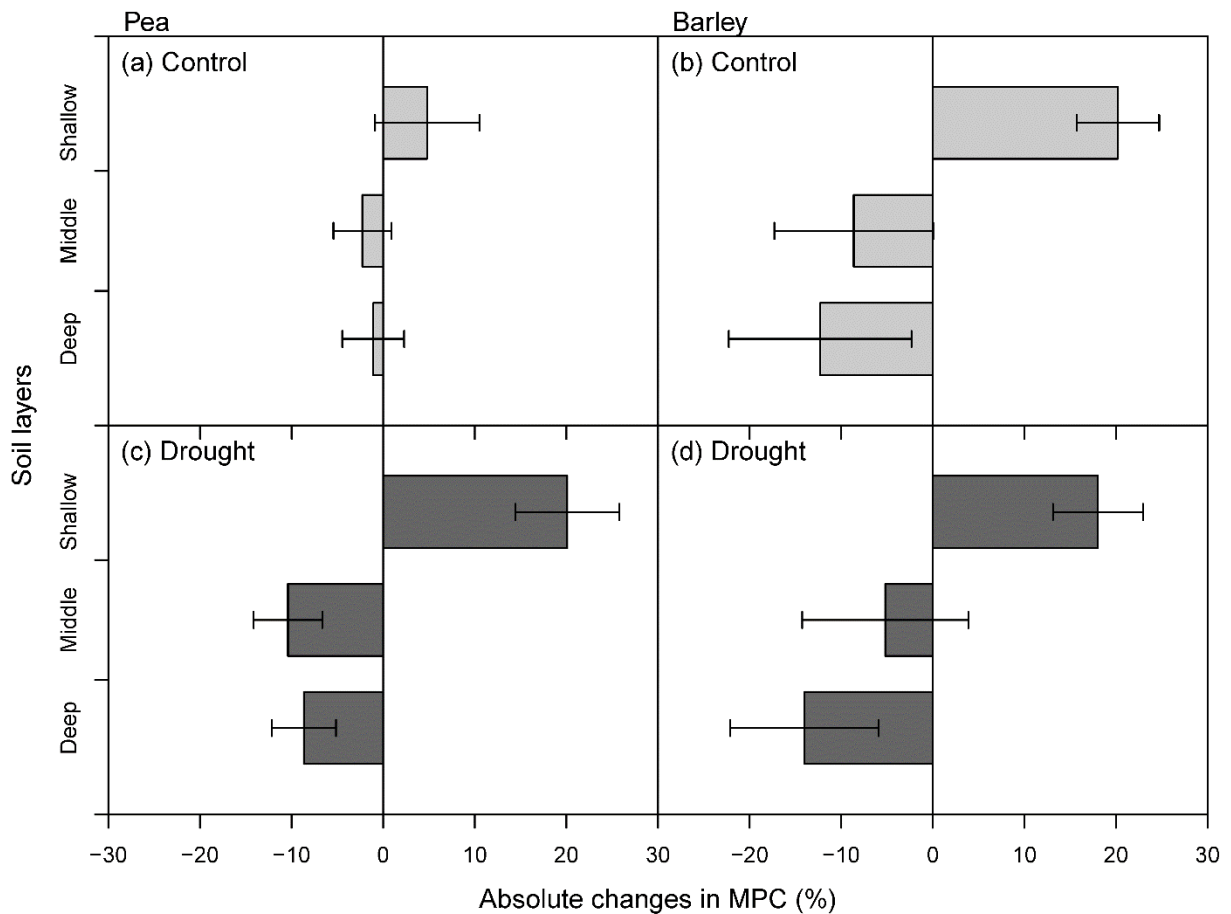
757

759 Fig. 5 Frequency density distribution of model outputs on the proportional contribution of soil water

760 to barley water uptake from shallow (0-20 cm, sum of 0-5, 5-10, and 10-20 cm), middle (20-40 cm,

761 sum of 20-30 and 30-40 cm), and deep (40-60 cm) soil layers under different cropping systems (a,

762 b) before the drought treatment on 7 May, (c, d) at the end of treatment on 25 June, and (e, f) after

763 treatment on 11 July in 2018. Frequency density was derived from 10 000 simulations at 2%

764 increment of mixing models using $\delta^{18}O$ for each subplot (Conv. for conventional, Org. for organic).

765 Data were pooled for all subplots in each cropping system. Symbols on the curves indicate the

766 median of the model outputs for each soil layer. Means and 1 SE (horizontal bars) of each cropping

767 system are given (n = 3-4).

768

769

Fig. 6 Absolute changes in median proportional contributions (MPC) to plant water uptake of pea
(a, c) and barley (b, d), calculated as the difference of MPC at the end (25 June; ET) and before the
drought treatment (7 May; BT), from three soil layers in control (a, b) and drought (c, d) subplots in
all cropping systems. MPC was derived from 10 000 simulations of mixing models using stable
water isotope data. Proportional contribution from the shallow layer is the sum of 0-5, 5-10, and 10-
20 cm depths, the middle layer is the sum of 20-30 and 30-40 cm depths, and the deep layer
represents 40-60 cm. Means and 1 SE (horizontal lines) are given (n = 14-16).

777