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1 **Impact of a Large-Scale Replacement of Maize by Soybean on**
2 **Water Deficit in Europe**

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10

11 **Abstract**

12 The EU imports large quantities of soybeans, mainly for livestock feed. However, there is a trend
13 to increase domestic soybean production and reduce imports. In this study, we investigate the
14 potential impact of an increased EU soybean cultivation on evapotranspiration (ET), water
15 deficit, and irrigation needs. We focus on the consequences of replacing maize with soybeans, as
16 both crops have similar cropping periods and high water demands. We implement a simple, well
17 established crop water model that estimates crop water deficit (*ETd*) as the difference between
18 simulated potential (*ETc*) and actual (*ETa*) ET. We apply this model over the EU from 2001 to
19 2020, using data on daily reference ET and precipitation, soil hydrological properties and three
20 different crop calendars. Results indicate that a maize-to-soybean conversion would result in an
21 average *ETd* increase of 49.0 ± 22.1 mm season⁻¹ across the EU. In the four countries of France,
22 Italy, Hungary and Romania, where most of the additional soybean production would be
23 allocated, crop water deficits would increase on average by 21-34% compared to that of maize,
24 following an increased *ETc* and/or decreased *ETa*. However, the decrease in *ETa* is largely due
25 to an assumed shorter root depth for soybean, while recent empirical results suggest that both
26 crops may actually have comparable root depths. Using the same root depth for maize and
27 soybean, the simulated average increase in *ETd* amounts to only 28.2 ± 18.3 mm season⁻¹. Our
28 results are sensitive to the choice of crop calendar, with reduced *ETd* for later sowing dates .
29

30 **Keywords**

31 soybean; maize; crop water deficit; Europe; evapotranspiration; modeling
32

33 **1 Introduction**

34 The European Union is importing about 30 Mt of soybean per year from the US and South
35 America, mainly for livestock feed (Debaeke et al., 2022). There is however a growing
36 awareness that these soybean imports drive agricultural conversion of savannahs and forests in
37 South America (Fearnside, 2001; Nepstad et al., 2014). Soybean production in the US, on the
38 other hand, is dominated by genetically modified (GM) cultivars (Harlander, 2002). On the
39 consumer side, there is a growing demand for soybean produced under environmentally friendly
40 conditions, which could be fulfilled by an increased domestic production of soybeans in the EU
41 (Zander et al., 2016). Indeed, although only 3% of soybean consumption in the EU is currently
42 covered by domestic production (Zander et al., 2016), soybean production has experienced a
43 significant growth in the EU over the last two decades. While in the years 2007-2009 the
44 production in EU27 was below 1 Mt soybean yr⁻¹, it reached 2.4-2.9 Mt soybean yr⁻¹ in the years
45 2015-2021 (European Commission, 2022). Over the same period, the soybean cultivated area
46 increased from 0.3-0.4 million ha to 0.8-1.0 million ha, respectively (European Commission,
47 2022). The EU supports the expansion of soybean and other leguminous crops in the framework
48 of the Farm2Fork strategy, which forms the central element of the European Green Deal to
49 achieve climate neutrality of EU agriculture by 2050, and which takes into account impacts on
50 the climate system caused outside of EU borders (European Commission, 2020).

51 In a recent study, Guilpart et al. (2022) have demonstrated the possibility to increase European
52 domestic soybean production substantially, satisfying at least half of the current demand in
53 Europe. Such an expansion of soybean cultivation may have environmental and agronomic
54 benefits. As a nitrogen-fixing crop, the integration of soybean into crop rotations may reduce the
55 amount of nitrogen fertilizers applied and increase the yield of the following crop (Zander et al.,
56 2016; Cernay et al. 2018). On the other hand, potential disadvantages of soybean cultivation are

57 related to high water demands (Grassini et al., 2015, Rüdelsheim and Smets, 2012) that may
58 increase agricultural water consumption for irrigation, or reduce groundwater recharge over
59 agricultural land. This impact of a soybean area expansion on the water cycle still needs to be
60 assessed at European scale to get a more complete picture on the potential advantages and
61 disadvantages of decreasing European soybean deficiency. On average, agriculture is responsible
62 for about one fourth of the water consumption in the EU, but becomes the dominant consumer in
63 southern countries of the EU and during summer months where/when crops have highest
64 irrigation needs, but also when the availability of surface water for abstraction is lowest
65 (Kristensen et al., 2018). EU environmental policies aim at preserving quantity and quality of
66 renewable freshwater resources (Kristensen et al., 2018), for which an intensification of
67 irrigation activities should be avoided as far as possible. On the other hand, the agronomic
68 benefits to irrigate soybean in Europe has been demonstrated as well, with yield increases of
69 ~40% under supplementary irrigation in Germany (Karges et al., 2022). Thus, it is possible that
70 decreasing soybean deficiency in Europe may go hand in hand with intensified irrigation.

71 In this study, we analyzed the potential impact of soybean expansion in Europe on crop water
72 deficit, irrigation demands and renewable freshwater resources. Following Martin (2015), we
73 assume that cultivation of soybeans expands primarily at the expense of maize, which is a
74 similarly thermophile and water demanding summer crop, and which is also mainly cultivated as
75 animal feed in the EU, although taking a different role in the diet of livestock (Karlsson et al.
76 2021). Note further that about 20% of the maize cultivated in the EU is already irrigated (Zajac
77 et al., 2022). Moreover, we assume that soybean will often be planted in rotations with maize,
78 which was shown to be a favorable combination with agronomical and ecological benefits
79 (Behnke et al., 2018; Grassini et al., 2015). Our assumption that the expansion of soybean
80 cultivation will mainly occur at the expense of maize is finally supported by similar
81 developments in the US during the mid-20th century (Langthaler, 2020). We simulate crop water
82 requirements of soybean vs. maize across Europe over the last two decades, using the model-
83 based approach developed by Allen et al. (1998) for the FAO (FAO56) and agricultural climate
84 and soil datasets developed by the Joint Research Centre of the EU. The FAO56 approach has
85 proven to be relevant for estimating potential and actual evapotranspiration (ET) of a wide
86 variety of crops. Due to its simplicity and efficiency, this approach has been implemented in
87 many software packages to support the planning of irrigation at field scale, as summarized in the
88 review by Pereira et al. (2020). The study by Sieber & Döll (2010) has demonstrated that this
89 approach can as well be applied at global scale.

90 We simulate the difference in crop water deficits for maize vs. soybean in Europe, for the areas
91 where a replacement of maize by soybean would be most productive according to the projections
92 of expected soybean yields by Guilpart et al. (2022). Finally, we critically evaluate the modeling
93 approach using three alternative crop calendars and performing a sensitivity analysis with
94 changing parametrisation of root depth, sowing and harvest date, and coefficients controlling the
95 theoretical crop water needs.

96 97 **2 Materials and Methods**

98 **2.1 Model Description**

99 Our model estimates daily potential and actual evapotranspiration (ET) based on the well-
100 established FAO56 double crop coefficient method (Allen et al., 1998). It requires daily values
101 of precipitation and reference ET (ET₀) as inputs. ET₀ is defined as potential ET of a
102 hypothetical reference crop similar to a well-watered, actively growing grassland with an

103 uniform height of 12 cm. ET_0 is directly available from agrometeorological datasets such as the
 104 one used in this study (see section 2.2). It was calculated using standard approaches such as the
 105 Penman-Monteith equation (Allen et al., 1998). Our model operates in two major steps: First, it
 106 calculates crop specific potential ET (ET_c) from ET_0 based on prescribed, ideal crop phenology
 107 (section 2.1.1). Second, it calculates the actual ET (ET_a) from ET_c based on a simple crop soil
 108 water budget model accounting for changing soil water storage through inputs of precipitation
 109 (P), and losses through ET, surface runoff and deep percolation (section 2.1.2).

110

111 **2.1.1 Simulation of Crop-Specific Potential ET (ET_c)**

112 Allen et al. (1998) proposed two different strategies to derive ET_c from ET_0 based on either a
 113 single or a double crop coefficient. The first strategy uses a single crop coefficient K_c (eq. 1) to
 114 compute ET_c from ET_0 . Standard values of K_c were derived from empirical studies as shown by
 115 Allen et al. 1998 (see below Table 1). In this approach, the growing season is divided into four
 116 consecutive crop growth stages: 1) initial stage from sowing until about 10% of vegetation cover
 117 (defined as fraction of ground covered by photosynthetically active vegetation) is reached; 2) the
 118 stage of crop development from ~10% vegetation cover to effective full cover; 3) the mid-season
 119 stage until the beginning of senescence; and 4) late season stage until harvest. Stage 3 covers the
 120 phenological stages of flowering, fruit development, and ripening of fruit and seeds (growth
 121 stages 6-8 on the BBCH scale), while stage 4 represents the phenological stage of senescence
 122 (stage 9 on the BBCH scale). For a given crop, K_c evolves over the growing period as follows.
 123 During stage 1, K_c remains at the initial value. During stage 2, K_c increases linearly from the
 124 initial to the mid-season value. During stage 3, K_c remains at the mid-season value. Finally,
 125 during stage 4, it linearly decreases to the end of the season value.

126 For our model, we used a second strategy based on the double crop coefficient approach
 127 proposed by Allen et al. (1998), which allows us to estimate evaporation and transpiration
 128 separately, as required to simulate the actual, water limited ET (see section 2.1.2). The crop
 129 coefficient K_c is split into the coefficients K_e and K_{cb} (eq. 2, Figure 1) to estimate potential
 130 evaporation E_c (eq. 3) and potential transpiration T_c (eq. 4) from ET_0 , respectively. Note that in
 131 our model set-up, K_e assumes no water limitation, and is thus the coefficient leading to E_c . As
 132 for K_c , tabulated values for K_{cb} were simply adopted from Allen et al. (1998), and K_e was
 133 calculated as the difference between these coefficients (see Table 1). Outside of the growing
 134 season, for which we assume bare soil, K_{cb} is zero and K_e is set to base-value of 0.30, following
 135 Allen et al. (1998).

136

137

$$138 \quad ET_c = K_c * ET_0 \text{ (eq. 1)}$$

139

$$140 \quad K_c = K_{cb} + K_e \text{ (eq. 2)}$$

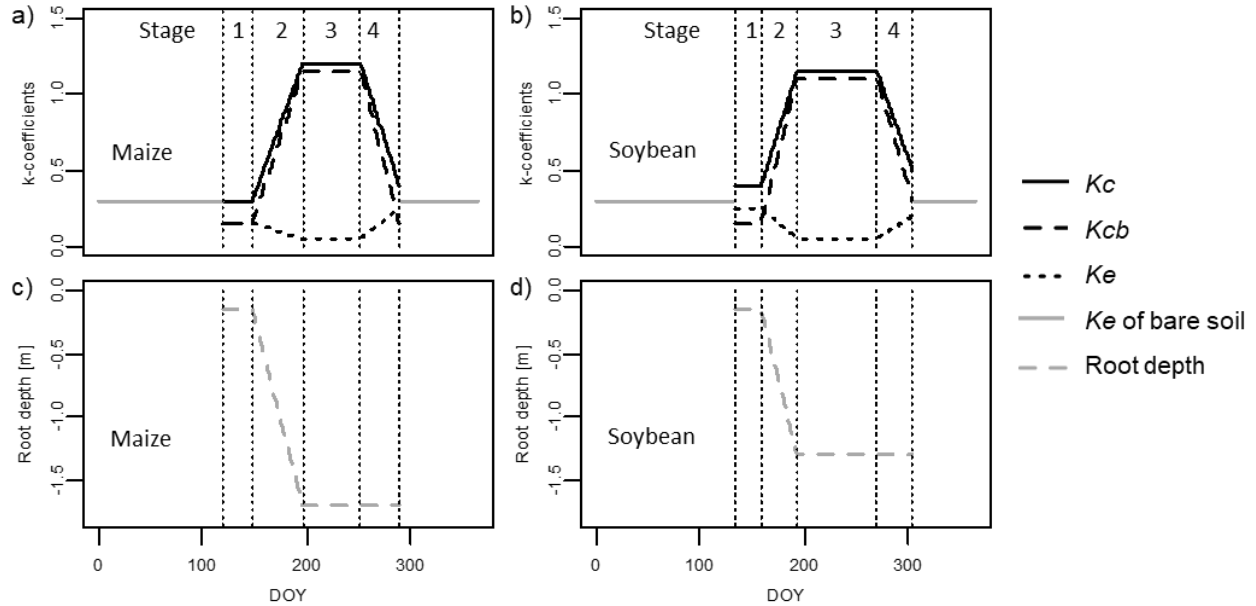
141

$$142 \quad E_c = K_e * ET_0 \text{ (eq. 3)}$$

143

$$144 \quad T_c = K_{cb} * ET_0 \text{ (eq. 4)}$$

145



146
147 **Figure 1.** Example of Crop Coefficients and Root Depth for Maize (a, c) and Soybean (b, d) over
148 the Annual Cycle and the Four Growing Stages from Sowing to Harvest. DOY: day of year.
149

150 **Table 1.** Crop Coefficients after Allen et al. (1998).

Stage	Maize			Soybean		
	K_c	K_{cb}	K_e	K_c	K_{cb}	K_e
1	0.30	0.15	0.15	0.40	0.15	0.25
3	1.20	1.15	0.05	1.15	1.10	0.05
end of 4	0.40	0.15	0.25	0.50	0.30	0.20

151
152 **Table 2.** Relative Length of Growing Stages (after Sieber and Döll 2010) Expressed in
153 Proportion of the Length of the Growing Season.

	stage 1	stage 2	stage 3	stage 4
Maize	0.17	0.28	0.33	0.22
Soy	0.15	0.20	0.45	0.20

154
155
156 The length of the different crop growth stages varies not only among crop types, but also
157 depending on cultivar, climate and sowing date (Allen et al. 1998). Here, we adopted the
158 approach implemented by Siebert and Döll (2010) for their application at the global scale where
159 the length of each crop stage changes proportionally to the total length of the growing season
160 defined according to different crop calendars (see section 2.2).
161

162 2.1.2 Simulation of Actual Evapotranspiration

163 The soil water budget model is based on a representation of the soil column as two
164 interconnected compartments, a topsoil compartment and a subsoil compartment with
165 corresponding soil water storages S_{top} and S_{sub} , respectively. For both compartments, the daily
166 change in soil water storage is simulated. S_{top} and S_{sub} are represented in units of mm. The depth
167 of the soil column D_{soil} equals the maximum root depth, which is set at 1.7 m for maize and at 1.3

168 m for soy following Allen et al. (1998). For the depth of the topsoil, we adopted the value of D_{top}
 169 = 0.15 m suggested by Allen et al. (1998). The depth of the subsoil D_{sub} is then simply derived as
 170 difference between D_{soil} and D_{top} .

171 Under the rain-fed conditions considered in our study, the topsoil compartment receives water
 172 inputs from infiltrating precipitation (eq. 5) equal to the difference between total daily
 173 precipitation P and surface runoff R . The top-soil loses water from actual evaporation Ea (Ea_{top})
 174 and actual transpiration Ta (Ta_{top}), but also from percolation to the sub-soil compartment (DI).
 175 The sub-soil compartment receives infiltrating water from the top soil (DI) as only input (eq. 6).
 176 Water loss from the subsoil is due to transpiration (Ta_{sub}) and deep-percolation (DP) of water out
 177 of the root-zone. Note that Ea only occurs from the topsoil. For all fluxes of water, we use units
 178 of mm d^{-1} .

179

$$180 \Delta S_{top} = (P-R) - Ea_{top} - Ta_{top} - DI \text{ (eq. 5)}$$

181

$$182 \Delta S_{sub} = DI - Ta_{sub} - DP \text{ (eq. 6)}$$

183

184 Surface runoff R is calculated based on the curve number approach described in the USDA
 185 National Engineering Handbook (USDA NRCS, 2004). This simple and robust approach has
 186 been used for decades, and was implemented into many contemporary crop water models like
 187 BUDGET (Raes et al., 2006), BEACH (Sheikh et al., 2009), SIMDualKc (Rosa et al., 2016), and
 188 AquaCrop (Raes et al., 2009). Deep infiltration DI occurs when the water storage of the top soil
 189 exceeds field capacity FC (given as volumetric water content), and is simply calculated as the
 190 difference between actual topsoil water content and topsoil water content at FC (eq. 7). The
 191 topsoil water content at FC is calculated by multiplying FC by the depth of the topsoil D_{top} .
 192 Similarly, deep percolation DP occurs when the water storage in the subsoil exceeds FC , and
 193 then equals the amount of water storage in excess (eq. 8). The subsoil water content at FC is
 194 calculated by multiplying FC by the depth of the subsoil column D_{sub} .

195

$$196 DI = S_{top} - FC \cdot D_{top} \text{ (eq. 7)}$$

197

$$198 DP = S_{sub} - FC \cdot D_{sub} \text{ (eq. 8)}$$

199

200 To calculate the actual evaporation Ea and transpiration Ta , we also follow Allen et al. (1998).
 201 Ea is limited by the actual water storage in the topsoil, and this effect is expressed by the unitless
 202 reduction factor Kr (eq. 9, 10). The minimum top soil water storage that can be reached until no
 203 evaporation occurs anymore is defined as half of the topsoil water storage at the permanent
 204 wilting point PWP (Allen et al., 1998). Note that other traditional large-scale approaches to
 205 model soil hydrology simply assume that soil moisture cannot drop below PWP (e.g. MacBean et
 206 al. 2020). However, empirical evidence exists that soil evaporation can drive topsoil moisture
 207 well below PWP in dryer climates (Agam et al., 2004), and assuming half of PWP as minimum
 208 limit for Ea appears thus more reasonable. Kr is calculated as the ratio between the actual
 209 amount of water that is available for evaporation and the maximum possible amount of water
 210 that could be available for evaporation (eq. 10), the latter being defined as difference between
 211 topsoil water storage at FC and half the topsoil water storage at PWP . Further, the amount of
 212 water in the topsoil, which is readily available for evaporation (readily evaporable water – REW),
 213 is taken into account in this equation. Note that REW refers to total amounts of water expressed

214 in mm, and does not represent volumetric water contents as FC and PWP . Values of FC and
 215 PWP are computed from spatial input data (section 2.2). Values of REW are estimated from the
 216 values of FC and PWP , which is possible as all three parameters depend mainly on soil
 217 texture. Allen et al. (1998) gives tabulated values for REW , FC , and PWP for different soil
 218 texture classes. Based on these tabulated data, we fitted eq. 11 which relates REW in mm to FC
 219 and PWP as volumetric water content (RMSE=0.6mm, rRMSE=7%). The empirical coefficient
 220 0.60 in this equation was accurately estimated (standard error of 0.01). We thus assume that the
 221 so estimated REW values are reasonable and consistent with the FC and PWP values used as
 222 model input.

$$223 \quad E_a = \min(K_r \cdot E_c, S_{top} - 0.5 \cdot PWP \cdot D_{top}) \quad (\text{eq. 9})$$

$$224 \quad K_r = \min\left(\frac{S_{top} - 0.5 \cdot PWP \cdot D_{top}}{(FC - 0.5 \cdot PWP) \cdot D_{top} - REW}, 1\right) \quad (\text{eq. 10})$$

$$225 \quad REW = 0.60 \cdot (FC - PWP) \quad (\text{eq. 11})$$

230 T_a reduces water content in both the top- and subsoil, depending on root depth D_{root} that changes
 231 over the season of crop growth. For stage 1, we assume that the roots are entirely within the
 232 topsoil, and no water is taken from the sub-soil ($D_{root}=D_{top}$). During stage 2, root depth linearly
 233 increases from D_{top} to D_{soil} , which equals the crop specific maximum root depth (see Figure
 234 1c,d). During stage 3 and 4, D_{root} equals D_{soil} . Outside of the growing season, T_a is zero.

235 Similarly to E_a , T_a is scaled to T_c based on a reduction factor, K_s , which depends on the ratio of
 236 actual water storage in the root zone S_{root} which is in excess to PWP , and the available water
 237 capacity, i.e. the difference between FC and PWP , over D_{root} (eqs. 12,13). The maximum
 238 possible value of T_a (eq. 12) is defined as the difference between the actual amount of water
 239 stored in the root zone S_{root} and the water storage over D_{root} at PWP , from which further the
 240 amount of water already lost to E_a is subtracted. S_{root} includes at least S_{top} , and the part of S_{sub}
 241 that is penetrated by roots (eq. 14). The calculation of K_s depends further on the daily values of
 242 ET_c ($ET_c = T_c + E_c$) (eq. 15) and a crop specific parameter p_{std} , which equals 0.55 and 0.50 for
 243 maize and soybean, respectively (Allen et al. 1998). The amount of transpired water that is taken
 244 from the top- ($T_{a_{top}}$) vs. subsoil ($T_{a_{sub}}$) (eqs. 5, 6) is linearly scaled to the proportion of S_{root} that
 245 can be attributed to the corresponding part of the soil column. Finally, ET_a is calculated as the
 246 sum of T_a and E_a (eq. 16), and the crop water deficit ET_d is calculated as the difference between
 247 ET_c and ET_a (eq. 17).

$$248 \quad T_a = \min(K_s \cdot T_c, S_{root} - PWP \cdot D_{root} - E_a) \quad (\text{eq. 12})$$

$$249 \quad K_s = \min\left(\frac{S_{root} - PWP \cdot D_{root}}{(1-p) \cdot (FC - PWP) \cdot D_{root}}, 1\right) \quad (\text{eq. 13})$$

$$250 \quad S_{root} = S_{top} + S_{sub} \cdot \frac{D_{root} - D_{top}}{D_{soil} - D_{top}} \quad (\text{eq. 14})$$

$$251 \quad p = p_{std} + 0.04 \cdot (5.0 - (T_c + E_c)) \quad (\text{eq. 15})$$

252

$$258 \quad ETa = Ta + Ea \quad (\text{eq. 16})$$

$$259 \quad ETd = ETc - ETa \quad (\text{eq. 17})$$

261 2.2 Model Input Data at European Scale

263 The model is applied at European scale using daily agroclimatology forcing data from JRC (see
264 Table 3 for reference, see Figure S1 giving overall workflow). More precisely, we use the daily
265 values of precipitation and ET0 over the period 1999-2020 available in this database. We
266 adopted the grid defined by the spatial reference and resolution (25km) of this dataset for our
267 simulations.

268 Information on permanent wilting point (*PWP*) and field capacity (*FC*) of soils was taken from
269 the high resolution (1 km) 3D soil hydraulic database provided by Tóth et al (2017) (see Table
270 3). The values of these parameters were first averaged over the soil profile for each 1 km grid
271 cell. To extract values representative for agricultural soils, this high resolution grid was then
272 masked by the areas of managed lands extracted from the GlobCOVER v2.3 dataset (Arino et al.,
273 2012), which is representative for the year 2009, before we calculated the arithmetic means of
274 *PWP* and *FC* for each 25 km cell of our model grid.

275 Each model grid cell was assigned to one of four soil hydraulic classes (< 10%, 10-20%, 20-
276 40%, >40% of clay, USDA NRCS 2004) which were required for the curve number approach we
277 used to estimate runoff in response to precipitation and soil moisture. For this, we first calculated
278 the average soil clay content per 25 km cell using the highly resolved information from the
279 Harmonized World Soil Database (HWSD) (Nachtergaele et al., 2010). Then, we classified the
280 grid cells accordingly.

281 Finally, we extracted data on sowing and harvest dates of soybean and maize from three different
282 crop calendars: MIRCA (Portmann et al., 2010), JRC-crop calendar (Sacks et al., 2010), and the
283 crop calendar of phase 3 the global gridded crop model inter-comparison project GGCM
284 (Jägermeyr et al., 2021), and assigned those information to each of the 25 km modelling grid
285 cells (Figures S1-S3). For the preparation of the spatial data sets, we used ESRITM's ArcGIS 10
286 with the SpatialAnalystTM extension.

287
288 **Table 3.** Data Sets Used in this Study.

Parameters	Data source	Resolution
Daily ET0, <i>P</i>	JRC MARS Meteorological Database v.3.1, https://agri4cast.jrc.ec.europa.eu/dataportal/	25 km
<i>PWP</i> , <i>FC</i>	3D soil hydraulic database (Tóth et al., 2017), https://esdac.jrc.ec.europa.eu/content/3d-soil-hydraulic-database-europe-1-km-and-250-m-resolution	1 km
Cropland mask	GlobCOVER v2.3 dataset (Arino et al., 2012), http://due.esrin.esa.int/page_globcover.php	0.3 km
Clay content	Harmonized World Soil Database (Nachtergaele et al. 2010), https://pure.iiasa.ac.at/id/eprint/17595/	~1 km
Crop calendars	MIRCA (Portmann et al., 2010), https://www.uni-frankfurt.de/45218023/MIRCA	~10 km
	JRC (Sacks et al., 2010), https://sage.nelson.wisc.edu/data-and-models/datasets/crop-calendar-dataset/ GGCM (Jägermeyr et al., 2021), https://zenodo.org/record/5062513#.Yv-T-d869aQ	~10 km ~55 km

Actual expected soybean yields	Guilpart et al. (2022), https://zenodo.org/record/6136216#.Yv-UMt869aQ	~10 km
Annual maize area	JRC (2017) Yearly modeled crop area in EU v1.0, https://agri4cast.jrc.ec.europa.eu/dataportal/	25 km

289

290

291 **2.3 Simulation Protocol**

292 We ran simulations for each of the three crop calendars. While the most recent one (GGCMI)
 293 gives a single calendar date for sowing and harvest per grid cell and per crop species, MIRCA
 294 provides months of sowing and harvest time without further specifying the day of the month,
 295 and the JRC crop calendar gives explicit ranges of possible sowing and harvest dates, as well as
 296 the usual length of the growing season. For MIRCA and JRC crop calendar, we ran simulations
 297 for three different scenarios: 1) starting at the earliest possible day of sowing, 2) starting at the
 298 latest possible day of sowing, and 3) starting in the middle of the sowing period. For each crop
 299 calendar and grid cell, we assumed the same length in days of the growing period across all
 300 scenarios. For the JRC crop calendar, the lengths were explicitly given, but for the MIRCA
 301 dataset, the length of the growing periods was assumed equal to the length from the middle of the
 302 month of sowing to the middle of the month of harvest. Accordingly, we ran simulations using
 303 up to three different lengths of growing season (i.e. one for each of the three crop calendars) and
 304 up to seven different sowing dates (see Table 5 and Figures S2-S4).

305 Simulations were run over the period 1999 to 2020. As initial conditions at the beginning of the
 306 simulation, soil moisture in both top and subsoil was assumed to be at field capacity. The
 307 changes in these storages were then simulated over the full 22-year period depending on inflows
 308 and outflows at daily time-step. Daily outputs of T_c , E_c , T_a , E_a , R , and DP were aggregated to
 309 totals per year and season. To avoid any possible impact from the starting conditions chosen for
 310 the simulation, the first two years of simulation were discarded from the analysis, retaining only
 311 simulation results for the 20-year period 2001-2020.

312

313 **2.4 Analysis of model simulations**

314 **2.4.1 Identification of potential areas for a maize-to-soybean conversion**

315 To identify the areas where a maize-to-soybean conversion would be efficient to increase
 316 soybean production, we combined two datasets (Table 3): (i) the European map of simulated
 317 actual soybean yields under historical (1981-2010) rainfed conditions established by Guilpart et
 318 al. (2022) (Figure 2a), and (ii) the European map of maize cultivated areas for the years 1975-
 319 2017 (JRC 2017) (Figure 2b). To ensure spatial consistency, we calculated for each grid cell of
 320 our modelling grid the average predicted soybean yield from the finer grid cells of the map by
 321 Guilpart et al. (2022). In contrast, the European map of maize cultivated areas was used directly
 322 because it was based on the same spatial grid as the one used for our simulations.

323 We assumed a maize-to-soybean conversion likely to occur where maize is currently grown and
 324 simulated soybean yield is equal or higher than $1.5 \text{ t ha}^{-1}\text{yr}^{-1}$. This choice is consistent with the
 325 study of Guilpart et al. (2022) that chose this minimum threshold to identify suitable areas for
 326 soybean cultivation. Model outputs were then analyzed for the four countries that contain 80% of
 327 areas meeting these criteria: France, Italy, Hungary, and Romania (Figure 2). To explore the full
 328 potential of a maize-to-soybean conversion, we considered for each model grid cell the
 329 maximum maize area across the time period 2000-2017.

330

331 **2.4.2 Effect of maize-to-soybean conversion on crop water deficit**

332 The effects of maize-to-soybean conversion on crop water deficit were analyzed through three
 333 key parameters: ETc , ETa , and ETd during the growing season. We computed these three
 334 parameters for both soybean and maize, and then changes in these parameters if maize is
 335 converted to soybean ($\Delta ETc_{m \rightarrow s}$, $\Delta ETa_{m \rightarrow s}$, and $\Delta ETd_{m \rightarrow s}$, see eq. 18 as example for $\Delta ETd_{m \rightarrow s}$).
 336 First, we analysed these parameters calculating averages (over gridcells) per country, year and
 337 crop calendar scenario, weighted by the maize areas to be converted to soybean. Then, we
 338 calculated ensemble means, i.e. averages per year and country, to analyse the interannual
 339 variability (IAV), which we expressed as standard deviation σ_{IAV} . In addition, we calculate
 340 standard deviations between the multi-annual averages of all parameters per country and crop
 341 calendar scenario (σ_{CC}) as a measure of uncertainty related to this model input. We used a paired
 342 t-test to check whether differences in ETd under soybean vs. maize were significant.

343 We analyzed the impact of crop calendar choice in more detail over the model grid, quantifying
 344 the effects of changes in sowing date (Δt_{plant}) and season length (Δt_{seas}) on simulated
 345 $\Delta ETd_{m \rightarrow s}$, $\Delta ETc_{m \rightarrow s}$, and $\Delta ETa_{m \rightarrow s}$. First, we calculated the average $\Delta ETd_{m \rightarrow s}$, $\Delta ETc_{m \rightarrow s}$, and
 346 $\Delta ETa_{m \rightarrow s}$ over the period 2001-2020 for each grid cell and for any possible combination of the
 347 seven crop calendar scenarios specified above (section 2.3). This yielded each 113,778 pairs of
 348 either $\Delta ETd_{m \rightarrow s}$, $\Delta ETc_{m \rightarrow s}$, and $\Delta ETa_{m \rightarrow s}$ as dependent variable and Δt_{plant} and Δt_{seas} as
 349 predictors. Then, we use multiple linear regression with random effect to quantify the effects of
 350 Δt_{plant} and Δt_{seas} on the independent variables and to calculate the corresponding partial
 351 correlations.

352

353 2.5 Sensitivity analysis of model simulations to parameters

354 Finally, we performed a deeper evaluation of our model approach, testing how sensitive
 355 simulation results were to different model parameters. There are three different groups of model
 356 parameters that determine the differences in ETa , ETc , and ETd between soybean and maize: (i)
 357 crop coefficients (Kc) (Tables 1 and 2), (ii) root depths (D_{root}), and (iii) crop calendars (CC).
 358 $\Delta ETa_{m \rightarrow s}$, $\Delta ETc_{m \rightarrow s}$, $\Delta ETd_{m \rightarrow s}$ can be broken down into the effects of each of these three groups
 359 of model parameters. For instance, $\Delta ETd_{m \rightarrow s}$ can be broken down into $\Delta ETd_{m \rightarrow s, Kc}$,
 360 $\Delta ETd_{m \rightarrow s, D_{root}}$, and $\Delta ETd_{m \rightarrow s, CC}$. To calculate these effects, we ran for each of these three groups
 361 of model parameters an alternative simulation for soybean with the corresponding model
 362 parameters set to the values used for maize. Then, we calculated the effects of each group of
 363 model parameters as differences between results from the standard simulation for soybean and
 364 the results from the corresponding alternative simulation for soybean, as demonstrated for the
 365 example of $\Delta ETd_{m \rightarrow s, D_{root}}$ in eq. 19, where $ETd_{s+D_{root}, m}$ represents the simulated ETd for soybean
 366 using the root depth of maize. We performed these alternative simulations and sensitivity
 367 analyses using the crop calendar GGCM1.

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$$369 \Delta ETd_{m \rightarrow s} = ETd_s - ETd_m \text{ (eq. 18)}$$

$$370 \Delta ETd_{m \rightarrow s, D_{root}} = ETd_s - ETd_{s+D_{root}, m} \text{ (eq. 19)}$$

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373 3 Results

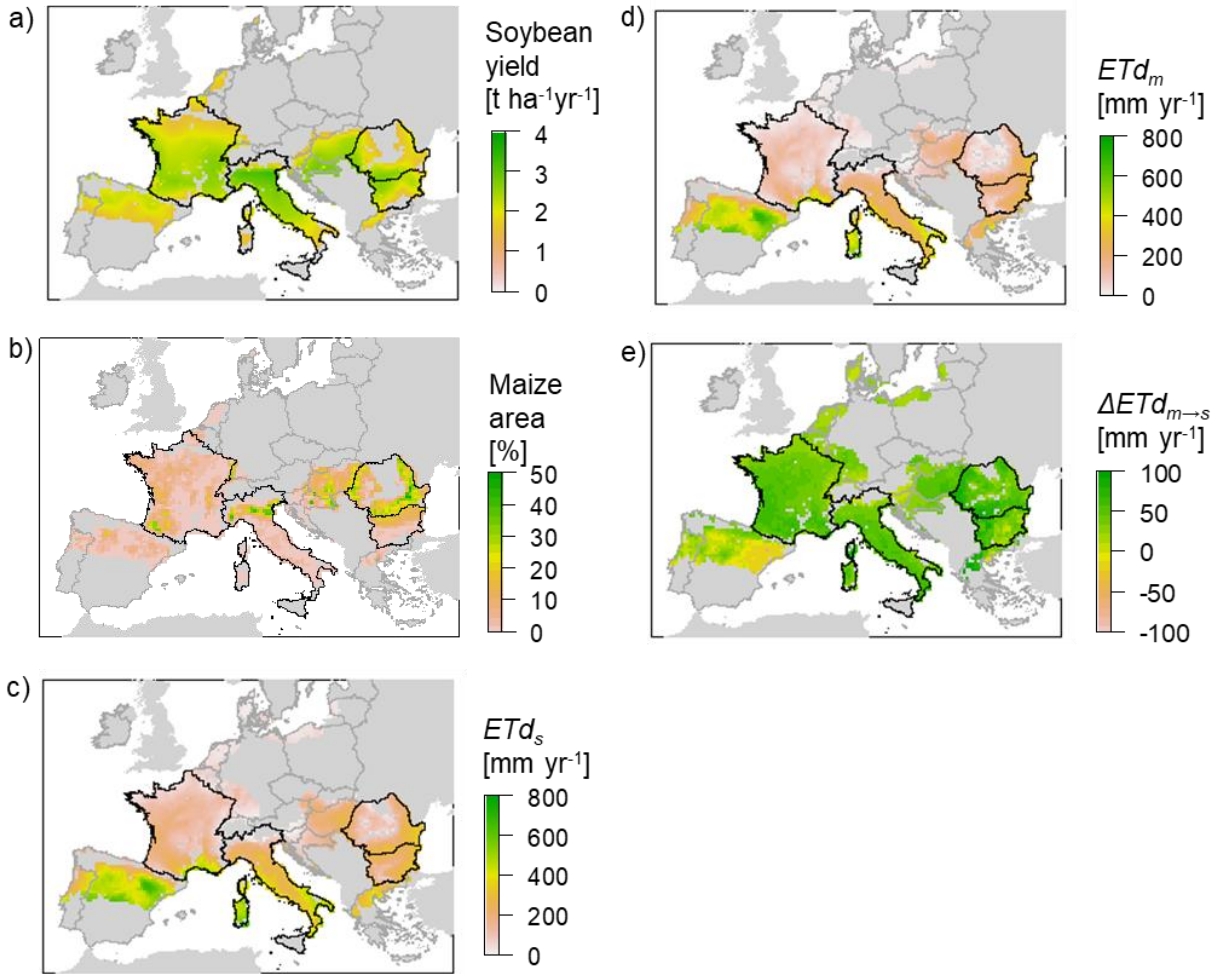
374 3.1 Simulated Crop Water Needs, Consumption and Deficit

375 3.1.1 Multi-year averages

376 Guilpart et al. (2022) predicted that soybean yields could reach $3.3 \text{ t ha}^{-1} \text{ yr}^{-1}$ in some regions of
 377 Europe (Figure 2a), which is consistent with actual yield observations in Europe (European

378 Commission, 2022) considering growing regions with less than 1% irrigated area (MIRCA crop
379 calendar). Considering only areas where a potential average soybean yield $\geq 1.5 \text{ t ha}^{-1}\text{yr}^{-1}$ was
380 predicted and where maize was grown between 2000 and 2017 (Figure 2b), we estimated a
381 potential increase in soybean production in the EU by 21.5 Mt yr^{-1} , i.e. $\sim 70\%$ soybean
382 consumption in the EU. This would be more than seven times higher than the maximum total
383 soybean production of 2.9 Mt yr^{-1} reported so far within the EU for the year 2018 (European
384 Commission, 2022). About 80 % of this additional soybean production replacing maize could be
385 attributed to France (4.5 Mt yr^{-1}), Italy (3.4 Mt yr^{-1}), Romania (6.2 Mt yr^{-1}) and Hungary (3.1 Mt
386 yr^{-1}).

387 Panels c and d in Figure 2 show average seasonal crop water deficit for soybean (ETd_s) and
388 maize (ETd_m), respectively. The spatial patterns in average ETd are very similar for both crops,
389 with a tendency for southward increasing values and highest ETd in Spain and Southern Italy.
390 Simulation results show that a maize-to-soybean conversion would increase ETd in 97.8 % of
391 current maize area, with exceptions mainly found in Spain and Portugal (Figure 2e). The
392 statistics of ETa , ETc and ETd under both crops in France, Italy, Hungary and Romania are listed
393 in Table 4. We find higher average ETd under soybean than under maize in all four countries,
394 with a national average predicted increase $\Delta ETd_{m \rightarrow s}$ ranging from $+44 \text{ mm season}^{-1}$ in Italy to
395 $+64 \text{ mm season}^{-1}$ in Romania (Table 4). The paired t-test proves that for each of the four
396 countries the differences between ETd_s and ETd_m is highly significant ($p < 0.001$), with a 95%
397 confidence interval around those mean values of less than $\pm 6 \text{ mm season}^{-1}$ (Table S4). Moreover,
398 taking for each of the four countries the 140 combinations of years ($n=20$) and crop calendar
399 scenarios ($n=7$) as a reference, $\Delta ETd_{m \rightarrow s}$ is positive in 91% of the cases for Italy, in 98% of the
400 cases in France and Hungary, and in all cases in Romania. In Hungary and Romania, increased
401 ETd under soybean ($+55$ and $+64 \text{ mm season}^{-1}$, respectively) appears to be mainly driven by
402 increased ETc ($\Delta ETc_{m \rightarrow s}$ of $+49$ and $+64 \text{ mm season}^{-1}$, respectively) (Table 4). On the contrary,
403 in Italy and France, lower ETa values ($\Delta ETa_{m \rightarrow s}$ of -40 and $-38 \text{ mm season}^{-1}$, respectively)
404 appear to be the main reason for higher ETd under soybean ($\Delta ETd_{m \rightarrow s}$ of $+44$ and $+50 \text{ mm}$
405 season^{-1} , respectively), while in Hungary or Romania the differences between mean ETa of both
406 crops are small or not significant, respectively (Table S4). Note that compared to France and
407 Italy, the average annual precipitation P is roughly about 200 mm yr^{-1} lower in Hungary and
408 Romania (Table 4), which may explain why ETa values are similar for both crops.



409
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411 **Figure 2.** Maps of (a) Predicted Soybean Yield (Guilpart et al., 2022) under Historical Climate
412 (1981-2010), (b) Maximum Areal Proportion of Maize Crop across EU (2000-2017), and
413 Simulated Crop Water Deficit (2001-2020) under (c) Soybean (ETd_s) and (d) Maize (ETd_m), and
414 (e) the Predicted Change in Crop Water Deficit when Maize is Converted to Soybean
415 ($\Delta ETd_{m \rightarrow s}$).

416 *All maps are masked to areas where maize was grown during 2000-2017, and where predicted
417 soybean yield $\geq 1.5 \text{ t ha}^{-1}\text{yr}^{-1}$. The simulated crop water deficits represent the ensemble mean of
418 the 7 different crop calendar scenarios. Dark grey lines give borders of EU27 countries (excl.
419 Cyprus). Black lines give the boundaries of France, Italy, Hungary and Romania (from left to
420 right), where most of the crop substitution is anticipated.

421
422

423 3.1.2 Inter-annual variability and seasonality

424 Figure 3 shows the time series of simulated ETd , ETc and ETa for soybean and maize in France,
425 Italy, Hungary and Romania over the period 2001-2020, with means and min-max values
426 obtained from the seven different crop calendar scenarios. Table 4 lists the ensemble means, the
427 interannual variability of simulations (IAV) measured by σ_{IAV} as well as the uncertainty related to
428 crop calendar choice measured by σ_{CC} for these four countries. We see that the IAV in ETd
429 follows that of ETc (Figure 3), but is higher than that of ETc (Table 4). This is because ETd is

430 calculated as the difference between in-season ET_c and ET_a , while year-to-year variations in
 431 these two variables show strong negative correlations (Table 4). These negative correlations
 432 reflect the fact that ET_c is higher in warm and dry years characterized by low soil moisture and
 433 insufficient precipitation to sustain an elevated ET_a .

434 For Italy, Hungary and Romania, we find significant correlations between the annual values of
 435 ET_a , ET_c , and ET_d vs. annual precipitation P (Table 4). For France, these correlations are not
 436 significant ($p > 0.05$) for soybean. This may be related to the fact that France shows the lowest
 437 IAV for P , ET_a and ET_d among these four countries. For all four countries and both crops, we
 438 find that the IAV in P is much more important than IAV in ET_a , ET_c and ET_d , and that its
 439 correlations with ET_a , ET_c , and ET_d are often significant, but substantially lower than one
 440 (Figure 3). Nevertheless, σ_{IAV} of ET_d is important, and amounts to about one third of the mean
 441 ET_d for soybean, and ranges between one third (Italy) and one half (Hungary) of the mean ET_d
 442 for maize (Table 4). But also the σ_{IAV} of $\Delta ET_d_{m \rightarrow s}$, is important and ranges from one fifth
 443 (Romania) to one half (Italy) of the average $\Delta ET_d_{m \rightarrow s}$. Interestingly, for none of the four
 444 countries does IAV in $\Delta ET_d_{m \rightarrow s}$ show any significant correlations with ET_d of any of the two
 445 crops.

446 To better understand the effect of differences in P on ET_a and ET_d , we have looked at both
 447 interannual and seasonal variations in fluxes (Figure 4). For detailed statistics of seasonal and
 448 interannual variability, see Table S1 in the supplemental information. A large fraction of annual
 449 P falls during the fallow period (Figure 4a,e). Moreover, the higher average annual P in France
 450 and Italy compared to Hungary and Romania is largely due to P during the fallow period, while
 451 during the four stages of crop growth considered in our model, the differences in average P per
 452 country are small compared to the IAV. More importantly, seasonality and interannual variability
 453 of losses of water to surface runoff R and deep percolation DP are strongly driven by P . If we
 454 subtract R and DP from P to get the net input of water that is available for ET_a (P^* , Figure 4b,f),
 455 we find that contribution of the fallow period to this net input is substantially reduced compared
 456 to P . Moreover, the IAV and the differences in average P^* among the four countries are strongly
 457 reduced compared to P .

458 The contribution of the fallow period to annual ET_a is small (Figure 4c,g). During this period, P^*
 459 generally exceeds ET_a , which means a gain in soil moisture. In contrast to the large differences
 460 in average P during that period among the four countries, the average gain of soil moisture
 461 during the fallow period ranges between 104 mm in Romania to 130 mm in France for soybean.
 462 For maize, average fallow period soil moisture gain is higher and ranges from 128 mm in
 463 Romania to 182 mm in France. In contrast, ET_a exceeds P^* over the four stages of crop
 464 development for both crops, which means that the soil moisture content is diminished during the
 465 growing period. During the third (flowering, fruit development, and ripening of fruit and seeds)
 466 and fourth stage (senescence to harvest), DP is zero (Table S1), which indicates that soil
 467 moisture becomes limiting in the third stage of crop growth. The third stage contributes most to
 468 ET_d during the crop season, followed by the fourth stage contributing most of the remainder
 469 (Figure 4d). For soybean, the third stage contributes between 74% (Romania) to 84% (Italy) of
 470 ET_d . For maize, the average contribution of the third stage to ET_d is a bit lower, ranging between
 471 64% in France and Romania to 68% in Italy and Hungary.

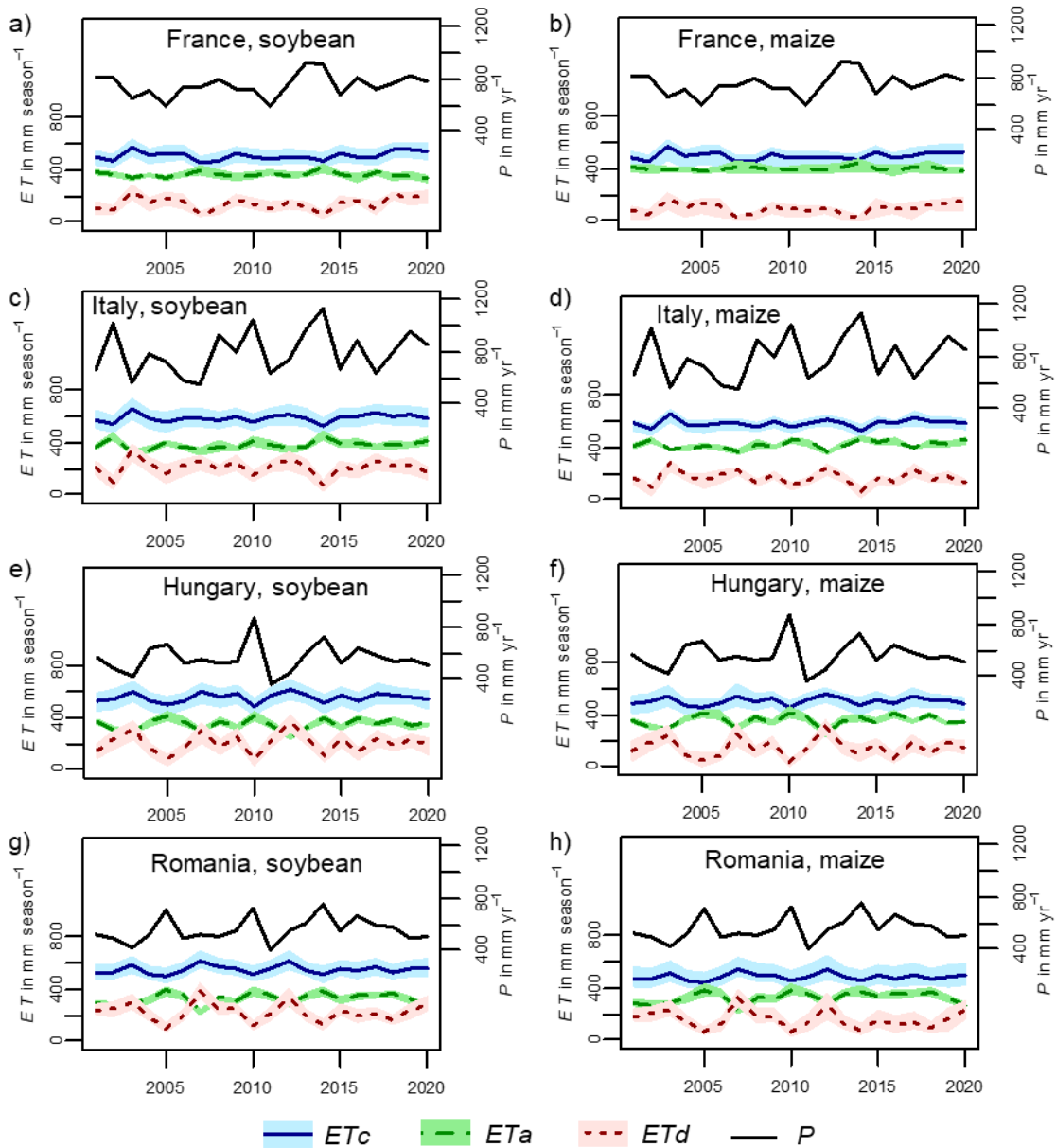
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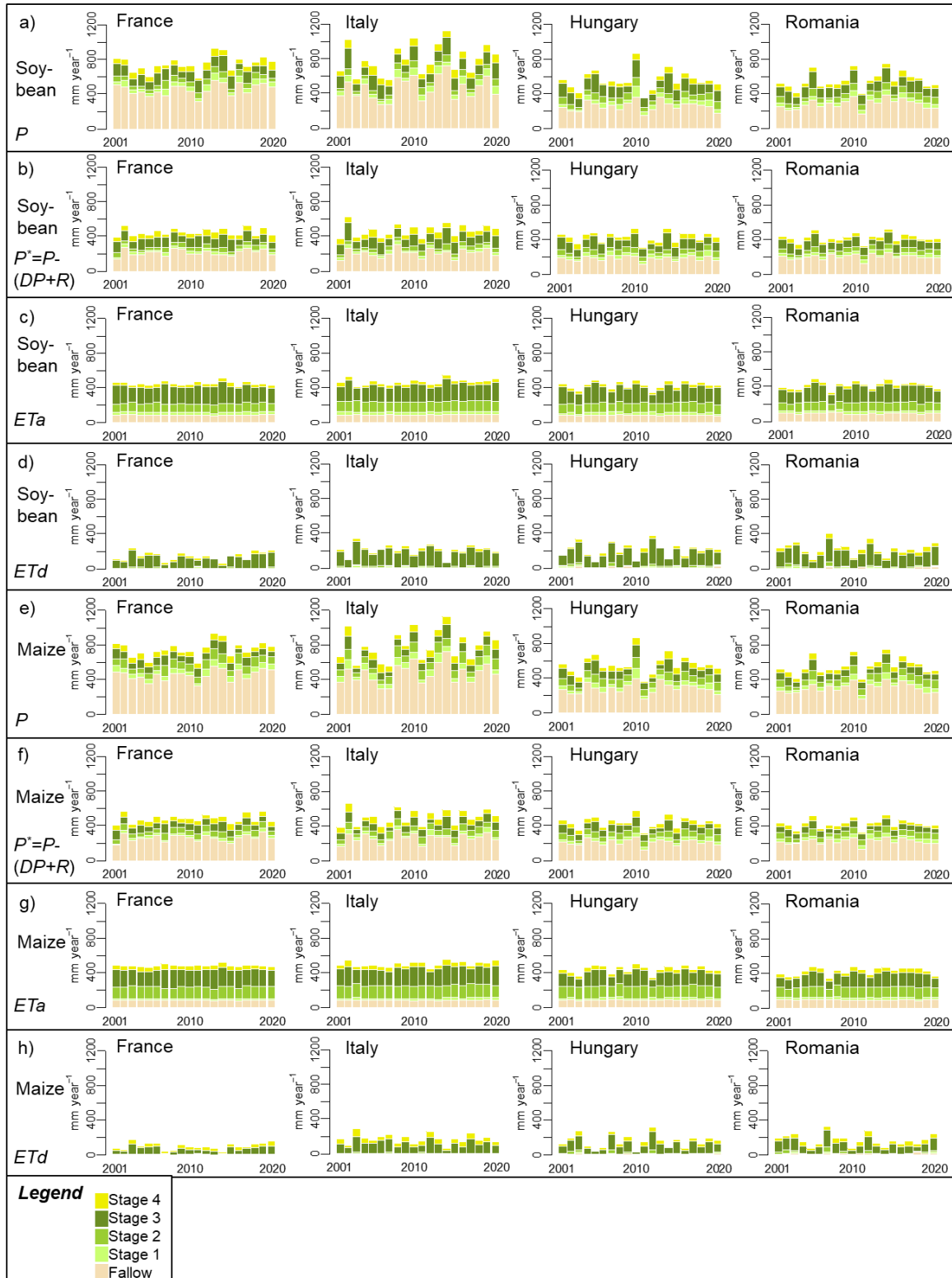
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Figure 3. Simulated potential and actual evapotranspiration (ET_c and ET_a , respectively), and crop water deficit (ET_d) for soybean and maize during the growing season vs. annual precipitation (P) in France, Italy, Hungary, and Romania. For ET_c , ET_a , and ET_d , the colored areas and the lines give the range and mean of results over seven different crop calendar scenarios.

487 **Table 4.** Summary of simulation results for France, Italy, Hungary and Romania over the period
 488 2001-2020: mean, standard deviation between years, standard deviation between crop calendars,
 489 and correlations between simulations.*
 490

Parameter	Unit	France	Italy	Hungary	Romania
ETc_s	mm season ⁻¹	513±31(39)	594±29(49)	555±36(49)	553±32(37)
ETa_s	mm season ⁻¹	366±21(13)	382±33(13)	351±42(12)	329±44(12)
ETd_s	mm season ⁻¹	146±48(27)	211±58(38)	204±75(38)	223±70(26)
ETc_m	mm season ⁻¹	501±31(39)	590±28(24)	506±33(46)	489±28(47)
ETa_m	mm season ⁻¹	404±13(16)	423±30(8)	357±43(11)	329±44(15)
ETd_m	mm season ⁻¹	97±39(24)	167±53(17)	149±72(35)	160±66(33)
$\Delta ETc_{m \rightarrow s}$	mm season ⁻¹	12±5(25)	4±6(36)	49±5(19)	64±4(32)
$\Delta ETa_{m \rightarrow s}$	mm season ⁻¹	-38±13(11)	-40±15(9)	-7±15(7)	0±9(14)
$\Delta ETd_{m \rightarrow s}$	mm season ⁻¹	50±16(17)	44±20(29)	55±17(14)	64±12(19)
P	mm yr ⁻¹	754±88	797±172	563±112	558±95
$ETc_s \sim ETa_s$	-	-0.67	-0.71	-0.86	-0.74
$ETc_m \sim ETa_m$	-	-0.52	-0.65	-0.78	-0.66
$ETc_s \sim P$	-	n.s.	-0.62	-0.71	-0.53
$ETa_s \sim P$	-	n.s.	0.71	0.68	0.65
$ETd_s \sim P$	-	n.s.	-0.72	-0.72	-0.64
$ETc_m \sim P$	-	n.s.	-0.66	-0.67	-0.50
$ETa_m \sim P$	-	0.58	0.71	0.57	0.57
$ETd_m \sim P$	-	-0.48	-0.75	-0.65	-0.59

491
 492 *Potential ET (ETc), actual ET (ETa) and crop water deficit (ETd) during cropping season of
 493 soybean (s) and maize (m) and the changes in these parameters when maize is converted to
 494 soybean ($\Delta ETc_{m \rightarrow s}$, $\Delta ETa_{m \rightarrow s}$, $\Delta ETd_{m \rightarrow s}$) are reported. The annual amounts of precipitation P are
 495 given for comparison. Values represent multi-annual means $\pm \sigma_{IAV}$ between years, while the
 496 numbers in brackets give standard deviation between crop calendar scenarios σ_{CC} . Finally,
 497 correlations between ETc and ETa , as well as between P and ETc , ETa , or ETd are reported as
 498 Pearson correlation coefficients.
 499
 500



501 **Figure 4:** Values of precipitation P , amount of P not lost to runoff R and deep percolation DP
 502 ($P^* = P - (DP+R)$), actual evapotranspiration ETa , and crop water deficit ETd for soybean and maize expressed
 503 by year and by season (four growth stages and fallow). For statistics with explicit values, see
 504 Table S1.
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3.2 Impact of Crop Calendars

The seven crop calendar scenarios used in this study differ substantially with regard to sowing dates and season length (Table 5, Figure S2-S4). The choice of the crop calendar scenario has an impact on the simulations of ETd , ETa and ETc for both maize and soybean (Figures S5 and S6), and thus on the simulated changes of these three parameters when maize is converted to soybean ($\Delta ETd_{m \rightarrow s}$, $\Delta ETA_{m \rightarrow s}$, and $\Delta ETC_{m \rightarrow s}$, respectively, Figures S7). The standard deviations between results per crop calendar scenario σ_{CC} are quite important, as can be seen from Table 4. The relative size of σ_{CC} range between nearly one third (Romania) and about two thirds (Italy) of the average $\Delta ETd_{m \rightarrow s}$ per country. To explore the impact of the crop calendar scenarios on the simulations, we fitted regression models relating average values of average $\Delta ETd_{m \rightarrow s}$, $\Delta ETA_{m \rightarrow s}$, and $\Delta ETC_{m \rightarrow s}$ over the 20 year simulation period (per grid cell) to the differences in sowing date (Δt_{plant}) and season length (Δt_{seas}) induced by the crop substitution (Table 6). Our regression analysis was able to explain more than half of the variability of $\Delta ETd_{m \rightarrow s}$, $\Delta ETA_{m \rightarrow s}$, and $\Delta ETC_{m \rightarrow s}$. The estimated parameters in the regression for $\Delta ETd_{m \rightarrow s}$ appear to be a nearly linear combination of the parameters in regressions of $\Delta ETC_{m \rightarrow s}$ and $\Delta ETA_{m \rightarrow s}$ due to the fact that $\Delta ETd_{m \rightarrow s}$ is the difference between $\Delta ETC_{m \rightarrow s}$ and $\Delta ETA_{m \rightarrow s}$, just as ETd is the difference between ETc and ETa . The intercepts of the three equations indicate the main crop substitution effect, independently from the differences in crop calendars. These intercepts show that soybean has a higher ETc but a lower ETa than maize during the growing season, both leading to a higher ETd for soybean than for maize. The positive regression parameter assigned to Δt_{seas} indicates a tendency for $\Delta ETd_{m \rightarrow s}$ to be higher if the maize-soybean conversion leads to a longer growing period. This is due to the fact that ETc and ETa tend to increase with the length of the growing season. According to the crop calendars used in this study (Table 5), there appears to be a tendency for soybean to have a growing season as long as or longer than maize. The effect of Δt_{seas} on $\Delta ETC_{m \rightarrow s}$ is however substantially stronger than on $\Delta ETA_{m \rightarrow s}$, as can be seen from the parameters in Table 6, and which indicates an increasing water limitation of ETa . Accordingly, Δt_{seas} has also a positive effect of $\Delta ETd_{m \rightarrow s}$.

536 **Table 5.** Average Sowing Dates and Length of Growing Season of Soybean and Maize in the
 537 four Countries where Maize-to-Soybean Conversions would be most Efficient.
 538

Crop calendar	Sowing date (DOY)							
	Soybean				Maize			
	Fra	Ita	Hun	Rom	Fra	Ita	Hun	Rom
MIRCA, first day	121	121	121	121	91	91	121	121
MIRCA, central date	135	135	135	135	105	105	135	135
MIRCA, last day	150	150	150	150	120	120	151	151
JRC, first day	116	116	116	105	88	86	87	86
JRC, central date	133	133	133	120	119	110	118	117
JRC, last day	151	151	151	137	150	135	150	149
GGCMI	122	122	121	113	101	96	117	116

Crop calendar	Length of growing season (days)							
	Soybean				Maize			
	Fra	Ita	Hun	Rom	Fra	Ita	Hun	Rom
MIRCA, first day	154	154	154	154	154	154	154	154
MIRCA, central date	154	154	154	154	154	154	154	154
MIRCA, last day	154	154	154	154	154	154	154	154
JRC, first day	170	170	170	148	169	161	153	122
JRC, central date	170	170	170	148	169	161	153	122
JRC, last day	170	170	170	148	169	161	153	122
GGCMI	160	160	162	124	156	149	138	120

539
 540 **Table 6.** Maize-to-Soybean Conversion Impact on ETd , ETc , and ETa as Explained by Changes
 541 in Sowing Date (Δt_{plant}) and Season Length (Δt_{seas}).^{*}
 542

Dependent variable	Intercept	Δt_{plant}		Δt_{seas}		RMSE
		Slope	r	Slope	r	
$\Delta ETd_{m \rightarrow s}$	61.2±0.4	-1.06±0.00	-0.57	1.25±0.01	0.52	30.6
$\Delta ETc_{m \rightarrow s}$	42.5±0.2	-1.65±0.00	-0.75	2.13±0.01	0.72	35.7
$\Delta ETa_{m \rightarrow s}$	18.2±0.3	-0.61±0.00	-0.70	0.90±0.00	0.68	12.5

543 ^{*}Results from multiple linear regression with random effect. Dependent variables, intercept and RMSE
 544 are in mm season⁻¹. Units of Δt_{plant} and Δt_{seas} are day of the year and days respectively. For both variables,
 545 the partial correlation r is given.
 546

547 Similarly, negative regression parameters assigned to Δt_{plant} indicate that $\Delta ETc_{m \rightarrow s}$ and $\Delta ETa_{m \rightarrow s}$
 548 decrease if soybean is sown later than maize and increase if soybean is sown earlier. This can be
 549 explained by the fact that the later soybean or maize are sown, the longer the growing season will
 550 extend into autumn, when ETc tends to be much lower than during the hot summer months.

551 Again, this effect is stronger for $\Delta ETc_{m \rightarrow s}$ than for $\Delta ETA_{m \rightarrow s}$, and thus Δt_{plant} has a negative effect
 552 on $\Delta ETd_{m \rightarrow s}$ as well. As we see from Table 5, there is a strong tendency for soybean to be sown
 553 later than maize, which has an attenuating effect on $\Delta ETd_{m \rightarrow s}$. Interestingly, the partial
 554 correlations for Δt_{plant} are about as strong as for Δt_{seas} , which means that both season length and
 555 sowing date have a similar importance in changing crop water needs, consumption and deficits.

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557 **3.3 Sensitivity Analysis to Model Parameters**

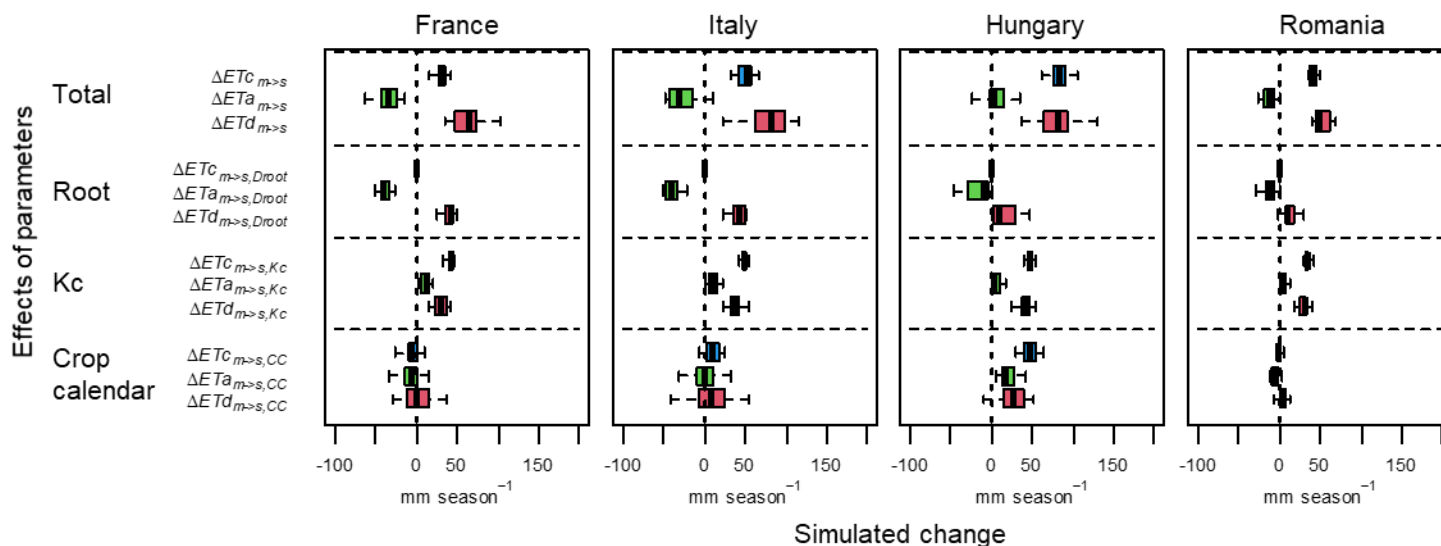
558 Figure 5 shows the sensitivity of simulated $\Delta ETA_{m \rightarrow s}$, $\Delta ETc_{m \rightarrow s}$, and $\Delta ETd_{m \rightarrow s}$ to different model
 559 parameters. Sensitivities were computed by replacing the parameter values of soybean by the
 560 values derived for maize. All sensitivity values (mean and σ_{IAV}) are shown in Table S2 in the
 561 supplemental material. Note that the crop calendar used for this sensitivity analysis, GGCMI,
 562 gives very similar sowing and harvest dates from soybean and maize, and for that reason the crop
 563 calendar appears to have a minor effect on the result (Table 5, Figures S2-S4). Only in Hungary,
 564 where the GGCMI crop calendar gives a growing season for soybean which is about 3 weeks
 565 longer than that for maize, we see an impact on $\Delta ETA_{m \rightarrow s}$ ($+21 \pm 11$ mm season⁻¹), $\Delta ETc_{m \rightarrow s}$
 566 ($+47 \pm 10$ mm season⁻¹), and $\Delta ETd_{m \rightarrow s}$ ($+26 \pm 18$ mm season⁻¹) (mean and σ_{IAV} , Table S2).

567 The different crop coefficients (Kc) appear to be the major reason for an increase in ETc under
 568 soybean, with values of $\Delta ETc_{m \rightarrow s, Kc}$ ranging from $+35 \pm 2$ mm season⁻¹ in Romania to $+48 \pm 3$ mm
 569 season⁻¹ in Italy (Table S2). In contrast, the shorter root depth for soybean vs. maize (1.3 m vs.
 570 1.7 m, respectively) appears to be the main driver of the simulated reduction in ETa when maize
 571 is converted to soybean. Interestingly, this effect seems to be much stronger in France and Italy
 572 ($\Delta ETA_{m \rightarrow s, Droot}$ of -39 ± 7 and -41 ± 8 mm season⁻¹, respectively), and relatively weak in Hungary
 573 and Romania ($\Delta ETA_{m \rightarrow s, Droot}$ of -17 ± 15 and -12 ± 8 mm season⁻¹, respectively, Table S2). For ETd ,
 574 it seems to be the combination of crop coefficients and root depth that lead to an increase when
 575 maize is converted to soybean, through the effect of these parameters on ETc and ETa ,
 576 respectively. The impact of the different crop coefficients on crop water deficit, $\Delta ETd_{m \rightarrow s, Kc}$,
 577 ranges from $+30 \pm 5$ mm season⁻¹ in Romania and $+30 \pm 9$ mm season⁻¹ in France to $+41 \pm 8$ mm
 578 season⁻¹ in Hungary. The impact of the difference in root depth on crop water deficit,
 579 $\Delta ETd_{m \rightarrow s, Droot}$, ranges from $+12 \pm 8$ mm season⁻¹ in Romania to $+38 \pm 8$ mm season⁻¹ in Italy (Table
 580 S2). Moreover, while differences in root depth are responsible for half of the total $\Delta ETd_{m \rightarrow s}$ in
 581 France and Italy, this parameter contributes for less than one fourth of the total $\Delta ETd_{m \rightarrow s}$ in
 582 Hungary and Romania.

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588 **Figure 5.** Simulated Change in Potential ET ($\Delta ETc_{m \rightarrow s}$, blue boxes), Actual ET ($\Delta ETa_{m \rightarrow s}$, green boxes) and Crop Water Deficit
 589 ($\Delta ETd_{m \rightarrow s}$, red boxes) when Maize would be Converted to Soybean, Quantitatively Detailing the Contributions of assumed Root
 590 Depth (D_{root}), Crop Coefficients (K_c), and Crop Calendars (CC).*

591 *Box plots represent the variability of annual values over the 20 year simulation period, with median, interquartile range and total
 592 range of values. For this sensitivity test, the GGCM crop calendar was used.

593 **4 Discussion**594 **4.1 Interpretation of results**

595 For our simulations, we assumed that all maize would be converted to soybean where the
 596 potential soybean yield would be $1.5 \text{ t ha}^{-1}\text{yr}^{-1}$ and higher. The four countries of France, Italy,
 597 Hungary and Romania would contribute 80% of that soybean production. We are well aware that
 598 a complete conversion of maize to soybean is not a realistic scenario. But assuming a conversion
 599 proportional to the total maize area in regions with a reasonably high expected soybean yield, the
 600 relative importance of these four countries seems valid for an analysis of the impact of a maize-
 601 to-soybean conversion on the climatic crop water demand/deficit within the EU. A sensitivity
 602 analysis using alternative thresholds of soybean yield of 1.0 and $2.0 \text{ t ha}^{-1}\text{yr}^{-1}$ shows that results
 603 presented in this paper are not affected by this threshold value (Table S3).

604 We found that the major part of crop water deficit occurs in the third of the four crop growth
 605 stages considered in our model (Figure S8), i.e. the mid-season from flowering to ripening of
 606 fruits and seeds, which would thus be the right time to irrigate. In France, Italy, and Hungary,
 607 the average timing of this third stage soybean development is between early July and mid-
 608 September. In Romania, the average timing of that stage is late June to the end of August. For
 609 maize, the duration of this third stage is about three weeks shorter, and ends already in the
 610 second half of August in all four countries. During these summer months, abstractions of water
 611 from surface- and groundwater bodies are increased, in particular for crop irrigation, while
 612 renewal of freshwater resources is reduced (Kristensen et al., 2018). This is even more the case
 613 in countries such as France and Italy where irrigation plays an important role (Kristensen et al.,
 614 2018).

615 For Italy, Hungary, and Romania we predict average crop water deficit for soybean of slightly
 616 above $200 \text{ mm season}^{-1}$, which compares well with water amounts applied for (close to) full
 617 irrigation of soybeans reported for fields in Croatia (Markovic et al. 2016) and Serbia (Pejic et al.
 618 2012), which lie geographically between these three countries. We saw that ETd would be higher
 619 under soybean than under maize in all four countries, but due to different reasons. We saw that
 620 the choice of crop calendars has a significant impact on simulation results. Nevertheless, under
 621 all scenarios, we simulate an increase in crop water deficit for a maize-to-soybean conversion. In
 622 Italy and France, $\Delta ETd_{m \rightarrow s}$ was mainly driven by $\Delta ETA_{m \rightarrow s}$. According to our simulations, a
 623 maize-to-soybean conversion would lower ETa by on average by $\sim 10\%$ in these two countries,
 624 which is comparable to what was found by Suyker & Verma (2009) in Nebraska under rainfed
 625 conditions. In Hungary and Romania, in contrast, $\Delta ETd_{m \rightarrow s}$ was mainly driven by $\Delta ETC_{m \rightarrow s}$, with
 626 a maize-to-soybean conversion increasing ETc by $\sim 10\%$. Interestingly, the predicted $\Delta ETA_{m \rightarrow s}$
 627 was minor to negligible in these two countries. That indicates that available soil water is more
 628 limiting in these two countries, not permitting for higher ETa under maize as predicted for
 629 France and Italy.

630 Our sensitivity analysis showed that positive $\Delta ETC_{m \rightarrow s}$ was largely caused by differences in crop
 631 coefficients, while the negative $\Delta ETA_{m \rightarrow s}$ was caused by differences in assumed root zone depth.
 632 The crop coefficients used by the FAO56 approach are based on numerous empirical findings.
 633 While some variability is to be expected among sites and varieties of maize and soybean, we can
 634 assume that the FAO56 parametrization is representative for European sites. Even for soybean,
 635 which is still not a very common crop in Europe, empirical studies from Hungary (Anda et al.,
 636 2020) and Croatia (Marković et al., 2016) confirm the applicability of FAO56 crop coefficients
 637 in Europe. The study by Anda et al. (2020) even showed that crop coefficients are very similar

638 between more and less drought tolerant varieties of soybean (*Sinara* and *Sigalia*, respectively,
639 Figure S9).

640 In contrast, generally assuming a rooting zone depth of 1.70 m for maize may appear unrealistic,
641 in particular in areas where root penetrable soil depth is limited. These values may represent
642 rather the maximum root zone depth under favorable soil conditions. Ordóñez et al. (2018)
643 suggest that in many areas, soybean and maize would rather develop a similar root depth. One
644 should thus be cautious regarding the effect of prescribed different root zone depth on our
645 simulation results. Using the default parameters of FAO56 approach, we simulate area weighted,
646 average ($\pm\sigma_{IAV}$) $\Delta ETd_{m \rightarrow s}$ of 49.0 ± 22.1 mm season⁻¹ across the EU, which represents an increase
647 in crop water deficit of 39% relative to maize. Using the same root zone depth of 1.30 m for
648 soybean and maize, simulated $\Delta ETd_{m \rightarrow s}$ is reduced to 28.2 ± 18.3 mm season⁻¹. This would
649 however still represent an increase in crop water deficit by 19% relative to maize.

650 As shown for the examples of Hungary and Romania, differences in root zone depth does not
651 seem to affect $\Delta ETd_{m \rightarrow s}$ in dryer climates where soil moisture availability is more limiting and
652 does not permit for higher ETa under maize even if the roots reach substantially deeper soil
653 layers. This also means that concerning the uncertainty arising from the assumed root depth, our
654 simulation results are more robust for Hungary and Romania than they are for France and Italy.

655

656 **4.2 Model Limitations and Perspectives**

657 The methodological approach of our study is simple and afflicted by a number of shortcomings,
658 which we would like to point out shortly. First of all, while we quantify the crop water deficit,
659 our approach is not able to quantify the effects of crop water deficit and realized, actual ET on
660 yields. Quantification of yield gaps caused by water shortage and of increases in yields through
661 irrigation would help to better assess the actual need for irrigation (Grassini et al. 2011b, 2014).
662 Similarly, while later sowing dates and shorter growing periods were found to reduce crop water
663 deficits, they may also decrease yields (Serafin-Andrzejewska et al. 2021; Mourtzinis et al.,
664 2019). Consideration of all costs involved in irrigation and changing revenues from increased
665 crop yield would be necessary to assess whether and in how far irrigation would be economically
666 worthwhile. Moreover, while our approach to calculate crop water deficit implies a baseline of
667 full irrigation, reasonable yield increases for soybean could still be achieved through deficit
668 irrigation (Karam et al., 2005), i.e. with less than full irrigation. Finally, costs of water and
669 market prices of crops may change over time (Kim & Kaluarachchi, 2016), which would make
670 such an assessment further challenging.

671 More importantly, our approach is limited in the sense that different management practices that
672 could affect water needs, consumption and deficits are not represented in our model. We used
673 standard parametrization of crop coefficients following FAO56 in combination with seven
674 different prescribed crop calendar scenarios. However, it is not clear how the choice of different
675 cultivars may affect actual sowing dates, length of growing season, and the actual crop
676 coefficients and root depths. This is especially the case under European conditions where
677 soybean is a relatively new crop and breeders are actively working to develop new varieties
678 adapted to local conditions, taking advantage of the wide range of variations in existing so-called
679 soybean maturity groups and associated lengths of the growing cycle (Kurasch et al. 2017).
680 Indeed, a locally adapted choice of cultivars with specific sowing dates would likely reduce crop
681 water deficits and related yield gaps, as shown by recent work on soybean in the US Corn Belt
682 (Andrade et al. 2022) and China (He et al. 2017). Further, we do not account for effects of
683 differences in sowing density that would affect ETc , ETa and ETd (Di Mauro et al. 2019,

684 Holshouser and Whittaker 2002). Also the effect of different tillage strategies and/or mulching
685 on soil evaporation losses is not taken into account. These management strategies would
686 however be an interesting lever to reduce crop water deficits (Jin et al., 2007).
687 Further, as discussed in the preceding subsection, our model is limited by assuming everywhere
688 the same maximum root depth, although rooting depth may be limited by root penetrable soil
689 depth or ground water table that may vary drastically between different locations (Chen et al.
690 2021). To our knowledge, no reliable dataset of root penetrable soil depth exists at European
691 scale, as soil depth is still very poorly predicted by digital soil mapping techniques (Chen et al.
692 2022). Future advances in mapping rootable soil depth in Europe would thus benefit strongly to
693 any work aiming at assessing future crop water needs in relation to the availability of renewable
694 water resources under climate change. Moreover, maximum root depth is not only limited by
695 rootable soil depth but also varies with climatic conditions (Benjamin and Nielsen 2006),
696 cultivars (Fried et al. 2018, Liu et al. 2021) and management practices (Fan et al., 2017; Ordóñez
697 et al., 2018). Important improvements to our current crop root modeling approach would be
698 needed to simulate such differences in root growth. This deserves further research. Our results
699 revealed a large impact of the maximum root depth parameter on actual ET and water deficit of
700 soybean. This reinforces the relevance of on-going work aiming at breeding soybean varieties
701 adapted to drought with a focus on roots traits (Bishop and Lynch 2015, Xiong et al. 2021).
702 Finally, our model follows a prescribed phenological development of the crop plants, not taking
703 into account delays in plant development, due to e.g. water shortage, and not allowing for
704 flexibility in sowing and harvest dates. Differences between existing crop calendars likely
705 represents a mix of a certain flexibility in sowing and harvest dates on one hand, and a limited
706 reliability of these datasets on the other hand. A better representation of the effects of
707 management practices on actual crop water needs and deficits could help to better assess the
708 implications of a maize-to-soybean conversion on irrigation demands.

709

710 **5 Conclusion and Outlook**

711 We predict an increase in crop water deficit following a maize-to-soybean conversion in France,
712 Italy, Hungary, and Romania. The country-average increases in crop water deficit are rather
713 similar, ranging between 44 ± 20 mm season⁻¹ in Italy and 64 ± 12 mm season⁻¹ in Romania and
714 representing an increase of about 21-34% of water deficit compared to rainfed maize. If the
715 entire area suitable for maize to crop substitution within the EU is taken as reference, the
716 increase in crop water deficit is even 39% relative to that of rainfed maize. The country-average
717 crop water deficit of new soybean fields would be substantially lower in France (~150 mm
718 season⁻¹) than for the other three countries (200-220 mm season⁻¹).

719 Our results have however to be seen critically in the light of the uncertainties existing on key
720 parameter values having strong impacts on water deficit estimations, in particular on maximum
721 root depth. Our estimates of an increase in crop water deficit through a maize-to-soybean
722 conversion only holds true if we assume a substantially higher max root depth for maize than for
723 soybean (as 1.7 m vs. 1.3 m following the default values of the FAO56 approach followed in this
724 study). There is however doubt that maize will often develop a higher root depth than soybean, in
725 particular if rootable soil depth is limited. Thus, more research on attained root depth of maize
726 vs. soybean across Europe is needed to better constraint the potential impact of maize-to-soybean
727 conversion on the crop water deficit. Finally, our simulation results suggest that crop water
728 deficits can be decreased by choosing later sowing dates, but probably at the costs of lower
729 water-limited yields. While this appears a promising strategy to decrease crop water deficit, an

730 assessment of how the choice of sowing dates would affect yields would help to better evaluate
731 the agronomic practicability.
732

733 **Appendix**

734

735 Table A1: Variables used in the study.

Code	Variable name
D_{root}	Depth of rootzone, time-variant
D_{soil}	Depth of soil column, fixed
D_{top}	Depth of topsoil, fixed
DI	Deep infiltration from top- to subsoil
DP	Deep percolation out of subsoil
Ea	Actual evaporation
Ea_{top}	Actual evaporation from topsoil
Ec	Potential evaporation
ET	Evapotranspiration
$ET0$	Reference ET (i.e. potential ET of a reference crop)
ETa	Actual evapotranspiration
ETc	Potential evapotranspiration
ETd	Crop water deficit ($=ETc-ETa$)
FC	Field capacity
FC_{top}	Field capacity of topsoil
Kc	Crop coefficient relating ETc to $ET0$
Kcb	Partial crop coefficient relating Tc to $ET0$
Ke	Partial crop coefficient relating Ec to $ET0$
Kr	Coefficient expressing limitation for Ea_{top} by water availability
Ks	Coefficient expressing limitation for Ta by water availability
P	Precipitation
p	Parameter used in the calculation of Ks
$pstd$	Crop specific constant used in the calculation of p
R	Surface runoff
REW	Water in topsoil readily available for evaporation
S_{root}	Water storage in root zone
S_{sub}	Water storage in subsoil
S_{top}	Water storage in topsoil
Ta	Actual transpiration
Ta_{sub}	Actual transpiration from subsoil
Ta_{top}	Actual transpiration from topsoil
Tc	Potential transpiration, crop specific
PWP	Permanent wilting point
PWP_{top}	Permanent wilting point in topsoil

736

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740

741 **References**

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