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Partitioning evapotranspiration of a drip-irrigated wheat crop: inter-comparing eddy covariance-, sap flow-, lysimeter- and FAO-based methods

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Abstract. *A precise estimate of the evapotranspiration (ET) partitioning is fundamental for determining the crop water needs and optimizing irrigation management. The plant transpiration (T) is generally considered to be the most desirable component, while reducing the soil evaporation (E) could be one of the most important water-saving actions in semi-arid agricultural regions. Given the lack of reference method to estimate the E/T partitioning of wheat crop, this study inter-compares four different methods based on eddy covariance, sap flow and lysimetry measurements and FAO modeling. The objectives are: i) to quantify the systematic and random uncertainty in E and T observations, ii) to evaluate the partitioning ratio (T/ET) at the daily/field scale and iii) to assess the performance of the FAO model over two drip irrigated wheat fields. Results indicate that despite the small surface sensed by mini-lysimeters, the partitioning ratio is evaluated more precisely (19% relative error) with lysimetry than with the other systems (any combination of eddy covariance, lysimetry and sap flow measurements). Moreover, stem-scale T measurements from sap flow sensors are subject to representativeness issues at the field scale, and to systematic errors during water-stress and senescence periods. The lysimeter-derived partitioning ratio increases from about 0.50 to 0.85 during the growth stage and rapidly drops towards 0 during senescence. Its dynamics is found to be significantly correlated ($R > 0.7$) with the 5-cm soil moisture. By comparing FAO simulations with observations, it is found that the FAO method overestimates T and underestimates E, while keeping satisfying ET estimates for drip irrigated wheat. This study suggests that different independent measurement techniques should be implemented to both quantify and reduce uncertainties in the T/ET ratio, and that accurate observations are still needed to improve the modeling of E/T components.*

38 **Keywords:** Wheat, evaporation-transpiration, sap flow, lysimeter, eddy correlation, FAO-56.

39

40 1. Introduction

41 A precise estimate of evapotranspiration (ET) is fundamental for determining the crop water
42 needs and subsequently for optimizing water management practices and irrigation regimes
43 (Allen et al., 1998). ET includes soil evaporation (E), plant transpiration (T) and the
44 evaporation of intercepted water. E and T processes in ecosystems are distinctly different. T is
45 always used for the calculation of plant productivity, unlike E that does not contribute to the
46 production. The partitioning of ET into gain and loss components for the ecosystem is
47 generally defined by the term "water use efficiency" or more precisely "water productivity".
48 In that sense, T is generally considered to be the most desirable component while E is
49 undesirable (Agam et al., 2012; Van Halsema and Vincent, 2012). Reducing E could actually
50 be one of the most important water-saving actions in semi-arid agricultural regions.

51 Given the growing concern about how to improve the water use efficiency of major irrigated
52 crops, efforts have been made to estimate the T/ET (or the E/ET) ratio of wheat crops
53 (Leuning et al., 1994; Denmead et al., 1996; Liu et al., 2002; Zhang et al., 2002; Kang et al.,
54 2003; Balwinder-Singh et al., 2011; Zhang et al., 2011; Kool et al., 2014). The E/T
55 partitioning of wheat crops is expected to change significantly across phenological stages
56 (Allen et al., 1998). A brief overview of the studies documenting the E/T partitioning of wheat
57 crops indicates that the T/ET ratio covers the 0-0.90 range (Kool et al., 2014).

58 One of the first estimates of this partition was derived by combining the E measured by
59 micro-lysimeters underneath the wheat canopy and the ET estimated by the energy balance
60 approach (Cooper et al., 1983; Leuning et al., 1994). The cumulated E to cumulated ET ratio
61 over the agricultural season was estimated at 0.32-0.38 for a wheat field in temperate climate
62 (Leuning et al., 1994). Later, Denmead et al. (1996) combined micro-meteorological (ET)
63 with micro-lysimetric (E) methods to estimate the E/ET ratio of a rainfed wheat field. The
64 daily ratio varied from 0.87 to 0.10 for a leaf area index (LAI) ranging from 0.2 to 3.7 m² m⁻².
65 Consistent results were obtained by Liu et al. (2002) and Kang et al. (2003) who combined
66 micro-lysimeters (E) and large-scale weighing lysimeters (ET) set up in a sub-humid and
67 semi-arid regions, respectively. The T/ET ratio ranged from 0, at the sowing date, to 0.80-0.90
68 at the growth peak and was found to be a function of LAI and surface soil moisture. More
69 recently, Balwinder-Singh et al. (2011) combined micro-lysimeters (E) and the water balance
70 approach (ET) and obtained an E/ET ratio ranging from 0.25 to 0.40 depending on the
71 phenological stage, the study year, and the mulch treatment (minimum and maximum values
72 corresponded to the mulched and non-mulched case, respectively). Zhang et al. (2011) and
73 Aouade et al. (2016) combined isotopic (E/T ratio) and eddy covariance (ET) measurements
74 over wheat fields in semi-arid climate. In the former study, the T/ET ratio was estimated at
75 0.83 and 0.60 on two dates separated by 11 days during the reproductive period. In the latter,
76 the T/ET ratio was estimated at 0.69 ± 0.08 on three successive days with wet conditions (just

77 after irrigation) and 0.80 ± 0.04 on two successive days with dry conditions during the
78 vegetative period.

79 In the prospect of investigating the E/T partitioning for assessing the water use efficiency of
80 wheat crops, continuous methods for measuring E or T separately are preferred rather than
81 one-off or temporary measurements. Although being time consuming, micro-lysimeters are
82 considered as being the most reliable method to measure E, as well as the T/ET ratio by using
83 an independent measurement of ET (and by neglecting intercepted water). The technique of E
84 measurements using micro-lysimeters is described in Boast and Robertson (1982) and
85 Leuning et al. (1994). The technique consists in extracting a small (usually 10-15 cm in
86 diameter) soil core, weighing manually the core, setting the core in situ underneath the canopy
87 for typically 1 day, weighing the core again, and changing the soil in the lysimetric cylinder
88 every 1 to 2 days to keep the conditions inside the lysimeter close to the outside field
89 conditions (Boast and Robertson, 1982). The change in mass of the core is directly
90 proportional to E, provided that the soil cores are replaced regularly (Daamen et al., 1993).
91 Since the first manual and passive micro-lysimeters, efforts have been made to improve the
92 system notably by using automated scales underneath the soil core (Grimmond et al., 1992;
93 Ucles et al., 2013; Agam, 2014) and by artificially adding or extracting water from the
94 cylinder bottom to mimic the real field conditions outside the micro-lysimeter (Brye et al.,
95 1999).

96 Another potentially useful technique is the sap flow measurement. This technique is quite
97 effective in estimating the T of orchards (Williams et al., 2004; Er-Raki et al., 2012;
98 Cammalleri et al., 2013) and row crops (Heilman and Ham, 1990; Thompson et al., 1997;
99 Agam et al., 2012). The advent of micro-sap flow sensors (Langensiepen et al., 2014; Miner et
100 al., 2017) now allows for applying the methodology to plants with stems of 3-mm diameter.
101 However, to the knowledge of the authors, none has been tested to specifically address the
102 E/T partitioning issue of wheat crops.

103 As an alternative to the above measurement methods, models can also be used to simulate E
104 and T separately. The most common and probably the most operational modeling approach is
105 the FAO dual crop coefficient model (FAO-2Kc, Allen, 2000). FAO-2Kc is extensively used
106 to estimate ET, E and T fluxes, especially for orchards (e.g. Er-Raki et al., 2010; 2012),
107 vineyards (e.g. Ferreira et al., 2012) and row crops (e.g. Ding et al., 2013). Although every
108 surface model is subject to uncertainties due to errors in its input parameters and
109 parameterizations, the point is that irrigation and meteorological forcing (via the atmospheric
110 evaporative demand) are strong constraints on the crop water budget. In addition, in the case
111 where irrigation volumes are precisely known at the crop field scale and meteorological data
112 are monitored nearby, the water budget of the FAO-2Kc model is forced by known and
113 spatially consistent input data, meaning that the output fluxes are simulated at the crop field
114 scale unlike many E/T/ET measurement techniques representative of a much smaller area. In
115 that sense, modeling tools like the FAO-2Kc are very useful as they provide independent
116 estimates of water budget components at a (field/daily) scale relevant to water management.
117 Nonetheless, few studies have addressed the E/T partitioning issue of field crops like wheat
118 using the FAO-2Kc (Kool et al., 2014).

119 *In summary, various E/T methods (micro-meteorology, water balance, lysimetry, isotopy)*
120 *have been implemented for wheat crops but three gaps are identified. First, each experimental*
121 *study has generally used only two independent methods (for E, T or ET), so that the*
122 *uncertainty in the estimated T/ET ratio cannot be evaluated. Second, the sap flow and FAO-*
123 *2Kc methods have not been tested to assess the E/T partitioning of wheat crops. Third,*
124 *continuous E/T/ET measurements across the agricultural season are rarely available, which*
125 *makes it difficult to assign the dynamics changes of T/ET to environmental factors*
126 *(phenological stage, LAI, surface soil moisture, etc.).*

127 To fill the gap, this study inter-compares the E/T estimates of four different methods based on
128 eddy covariance, sap flow and lysimetry measurements and FAO-2Kc modeling. The
129 objectives are three-fold: 1) to propose a methodology for quantifying uncertainties in E/T/ET
130 fluxes 2) to estimate at the daily scale the partitioning ratio (T/ET) of two drip irrigated wheat
131 fields, and 3) to assess the performance of the FAO-2Kc model. To this end, two drip-
132 irrigated winter wheat crops in central Morocco are equipped with an eddy covariance tower
133 (ET) and sap flow sensors (T). One field crop (reference wheat field) is irrigated according to
134 the FAO crop water needs, while the other crop field (controlled stress field) undergoes
135 several stress periods when irrigation is deliberately cut. Two autonomous and tension-
136 controlled mini-lysimeters are installed in the controlled stress field, one measuring ET and
137 the other measuring E alone.

138

139 **2. Materials and methods**

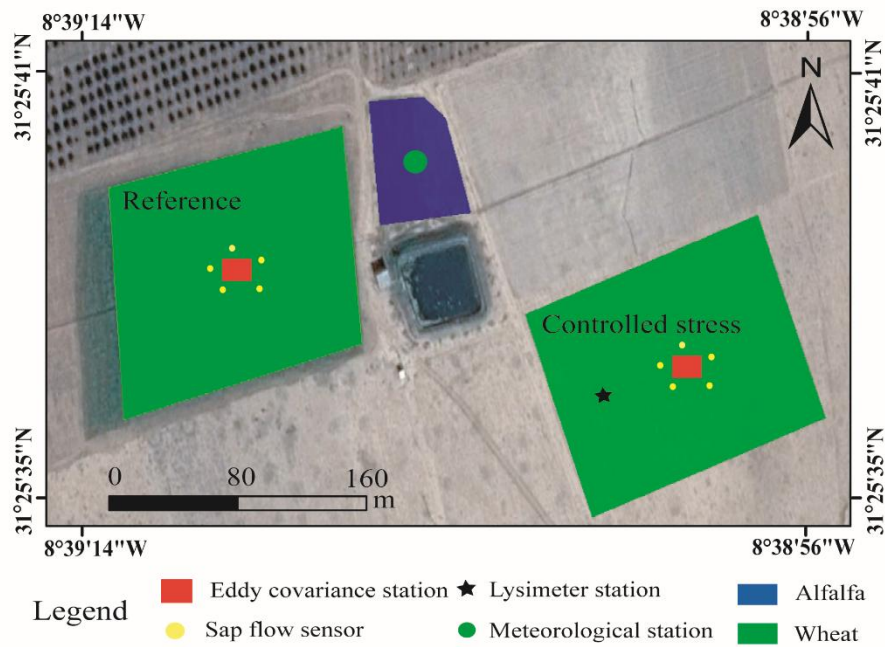
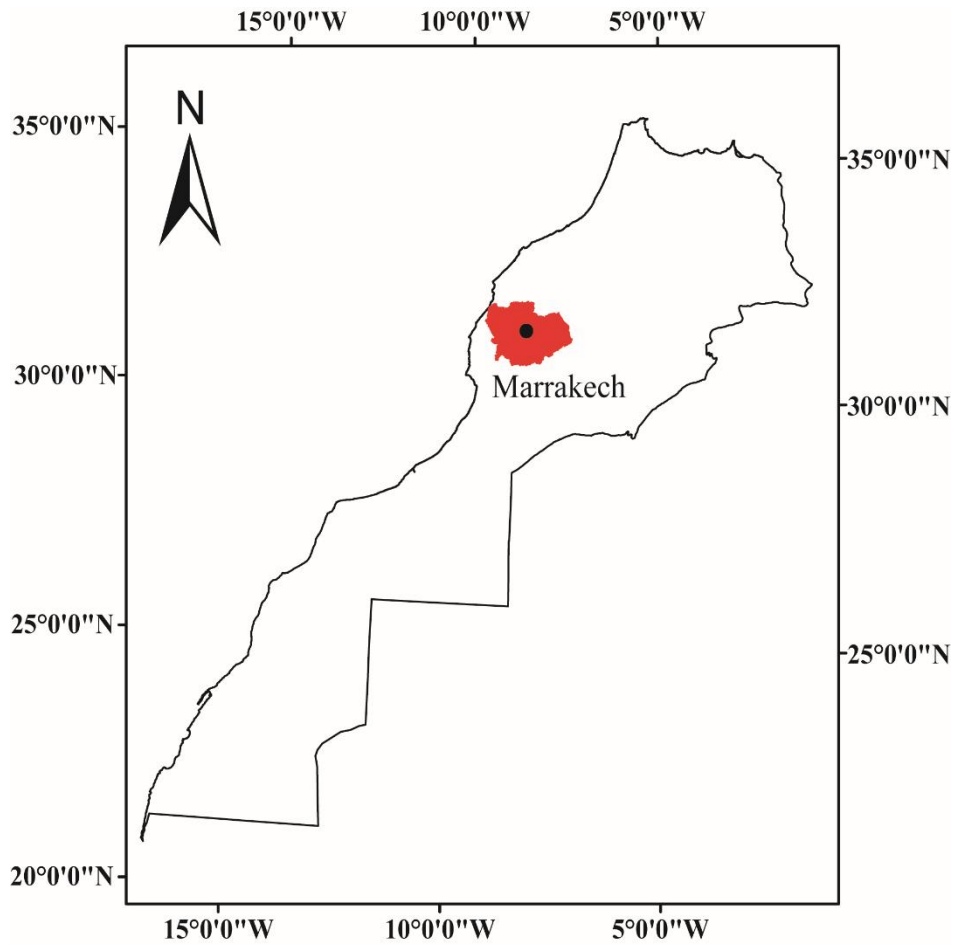
140

141 **2.1 Study area**

142 The study site (31°25'36.4"N, 8°39'05.9"W) is located in the Haouz plain (centre of
143 Morocco), about 70 km west of Marrakech city (Figure 1). The region is characterized by a
144 semi-arid to arid climate with low precipitation (< 250 mm/year) against a strong reference
145 evapotranspiration ET_0 of about 1600 mm/year (Jarlan et al., 2015). In the case of wheat,
146 historically, the most common irrigation method in the Marrakech region is flood irrigation.
147 Recently, with the encouragement given by the Green Morocco Plan (PMV, 2013) to optimize
148 the crop water use efficiency, a few farms have opted for the use of drip irrigation instead of
149 flood irrigation.

150 In this study, conducted during 2016-2017 wheat season, we used two fields of winter wheat
151 (*variety Karim*) of about 1.5 ha each (Figure 1). Wheat was sown on both plots on November
152 27th, 2016 by using an automatic seed drill with a distance of 15 cm between each sowing
153 line. Fields are irrigated by drip method. The distance between irrigating tubes was 0.7 m and
154 the distance between drippers was 0.4 m. The flow rate of each dripper is 2 l/hour, which is
155 equivalent to 7.14 mm/hour. During this experiment, the mean duration of irrigation was 1
156 hour 45 minutes equivalent to 12.53 mm.

157 Both fields had the same technical itineraries except that one field (reference field) had been
158 irrigated according to the FAO crop water requirements while the other field (controlled stress
159 field) had been stressed voluntarily during three periods. Each field was equipped with an
160 eddy covariance station (installed on November 24th, 2016) and sap flow sensors (installed on
161 March 8th, 2017). Also, the surface net radiation R_n (which is the net effect of incoming and
162 outgoing long and short-wave radiation) was measured by using CNR1 sensor, the soil heat
163 flux density was measured at 5 cm depth by using heat flux plates (HFT3-L), and the soil
164 moisture content at different depths by using TDR sensors. In addition, the controlled stress
165 field was equipped with a lysimeter station (installed on November 22nd, 2016). Irrigation
166 volumes are precisely collected at a single valve by a flowmeter. Moreover, an automatic
167 weather station was set up, over an alfalfa near the studied wheat fields, to provide continuous
168 measurements of meteorological forcing and ET_0 estimates.



169

170 Figure 1: Location of the Tensift basin in Morocco and set up of the experiment over the two
 171 (reference and controlled stress) drip-irrigated wheat fields.

172

173 2.2 Eddy-covariance (EC) station:

174 *The EC system was installed at the centre of each wheat field at a height of 2.58 m. The*
175 *choice of the installation height resulted in a compromise between two constraints: 1)*
176 *sampling within the field for a range of wind directions and 2) measuring at least 1.7 m above*
177 *the top of the canopy.* The EC consists of a 3D sonic anemometer (CSAT3, Campbell
178 Scientific Ltd.) that measures the three components of wind speed, and a krypton KH₂O
179 hygrometer that measures the rapid fluctuations of atmospheric water vapor. Raw data
180 sampled at a rate of 20Hz are used to calculate sensible (H_{EC}) and latent heat (LE_{EC}) fluxes
181 offline using the EC processing software 'ECpack' (Van Dijk et al. 2004), developed by the
182 Meteorology and Air Quality Group, Wageningen University. The correlation between
183 observed available energy (–net radiation minus ground heat flux) and the sum of turbulent
184 fluxes ($H_{EC} + LE_{EC}$) is very significant for both controlled stress ($R^2=0.88$) and reference
185 ($R^2=0.93$) field. However, the slope of the linear regression is 0.55 and 0.44, respectively,
186 which result in a systematic underestimation of turbulent fluxes by EC system. Therefore, a
187 correction of H_{EC} and LE_{EC} is applied while preserving the available energy using Bowen's
188 ratio (Twine et al., 2000). For a mean wind speed of 1.95 m/s and a direction of 58 degrees,
189 the fetch corresponding to the EC equipment measurements is 50 m long and 32.5 m wide and
190 this for a total contribution of 95%.

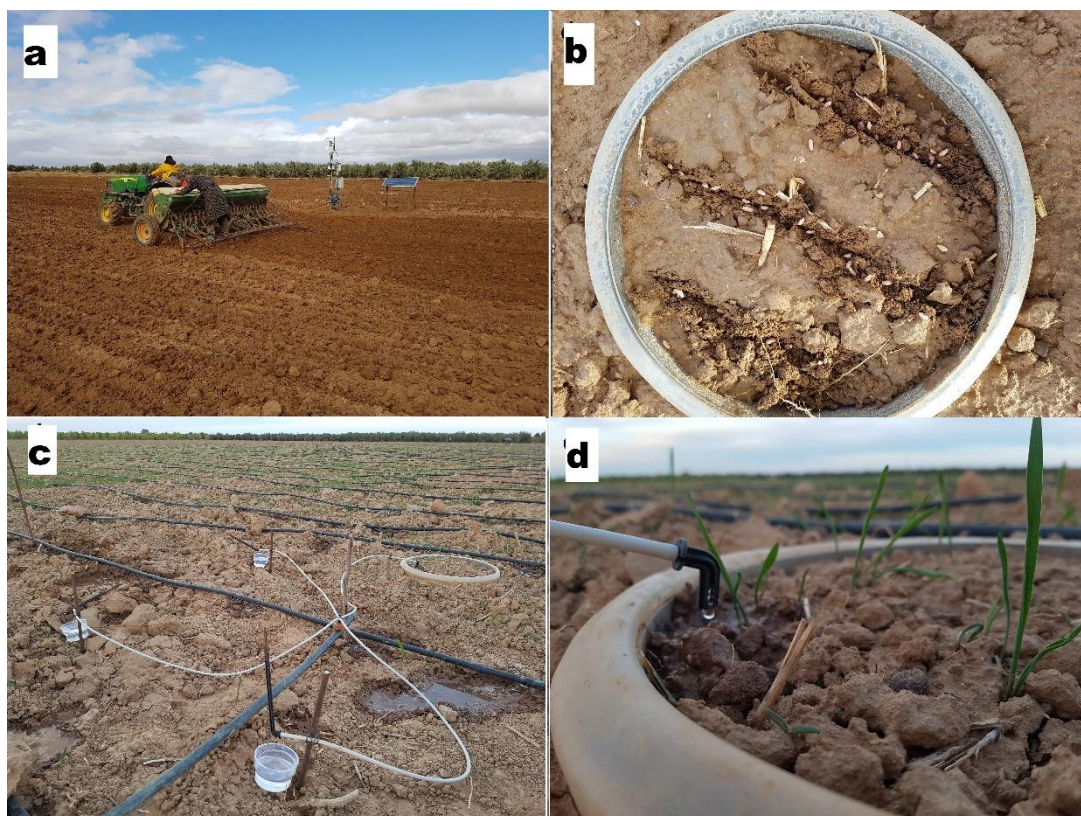
191 The difference obtained between ($R_n - G$) and uncorrected ($H_{ec} + LE_{ec}$) is significant. Such
192 difference is explained by the combination of several factors. First, the underestimation of
193 fluxes measured by the Eddy covariance system can be due to the attenuation of turbulent
194 signals at sufficiently low or high frequencies (Moore, 1986). Second, the source area of the
195 sensors that measure the available energy (net radiation and conductive flux in the ground) is
196 very small compared to that of the Eddy covariance system which can be changed rapidly
197 depending on wind speed and direction and surface conditions. *Third, the heat storage above*
198 *the soil heat flux plate measurements was not considered. The rationale is that this study*
199 *focuses on daily fluxes and that the heat storage at the daily time scale is zero. In addition,*
200 Scott et al. (2003) found that the energy stored in biomass represents about 5% of the
201 available energy, which could explain part of the non-closure of the energy balance.

202 The 30-min LE data is hence corrected at each time step, and an average is applied over 24
203 hours to estimate the daily LE. Finally, daily LE is converted from W/m^2 to mm/day by
204 multiplying it by a factor of 0.035 (Table 3, FAO-56, Allen et al., 1998).

205 2.3 Lysimeter (Lys) station:

206 A Smart Field Lysimeter (SFL) station was installed in the controlled stress field. The SFL
207 was connected to two mini-Lys (30 cm in diameter): one 30 cm depth Lys and one 90 cm
208 depth Lys. As this study focuses on the E/T partitioning, the two Lys were prepared to
209 measure separately the E and ET terms (see appendix A). The 30-cm deep Lys was dedicated
210 to measure E (E_{Lys}), while the 90-cm deep Lys was dedicated to measure ET (ET_{Lys}). For
211 simplicity the E measured by the 30-cm Lys and the ET measured by the 90-cm Lys are both
212 referred to ET measurements below (with T equal to 0 in the former case).

213 Both Lys were sown (see Figure 2.d) on November 27th 2016, respecting the density (30
214 grams/m²) of seedlings that were applied to the entire field by the automatic seed drill (Figure
215 2a). Special attention was paid to the irrigation of both Lys. Due to representativeness issues,
216 the irrigation flow rate at the Lys surface had to be reduced to approximately one fourth of the
217 original dripper flow rate (2 l/hour). This value comes from a simple computation of the
218 surface area fed by one dripper in field conditions: drip pipes are separated by 70 cm and
219 drippers are set every 40 cm along each pipe, so that the elementary surface for each dripper is
220 0.28 m², which is approximately 4 times the surface area (0.07 m²) of the SFL Lys. The
221 irrigation system of Lys consisted of 1) an autoregulated dripper (connected to the nearest drip
222 pipe of each Lys) designed to keep a flow of 2 l/hour and 2) a distribution network (connected
223 to the autoregulated dripper) with 4 exits, designed to distribute equally the inflow, that is to
224 obtain a stable outflow of 0.5 l/hour at the Lys level (Figure 2c). A flow rate of 0.5 l/hour
225 ensures that the Lys top boundary conditions are representative of the whole crop field (Figure
226 2d).



227

228 Figure 2: a) Automatic seed drill used to sow wheat. b) Surface of the SFL Lys sowed by
229 wheat seeds. c) The primary dripper flow (2 l/hour) is divided by 4 to make the Lys upper
230 boundary condition representative of the whole crop field, and the flow rate at Lys level (0.5
231 l/hour) is checked at the beginning of the experiment. d) The secondary dripper (0.5 l/hour)
232 feeding the Lys.

233 Both Lys measured ET (including E and T components) until March 1st, 2017. On March 2nd
234 2017, the herbicide "roundup" was applied to the 30-cm deep Lys. Roundup is a systemic
235 product that kills vegetation and roots but keeps the structure of the vegetation in place. This

236 experimental strategy was undertaken 1) to remove the T component over the 30-cm deep Lys
237 and 2) to reproduce as much as possible the shielding effects of wheat canopy on the E.
238 Hence, Lys-derived E and ET are available from March the 3rd 2017 until the end of the
239 season.

240 2.4 Sap flow (SF):

241 The stem heat balance (SHB) method for measuring sap flux relies on i) the addition of a
242 given thermal energy at a point of the stem, trunk or branch of a plant, and ii) the
243 measurement of the dissipation of this energy by convection via the SF of the stem. The SF is
244 strongly related to T, which accounts for as much as 99% of the soil water uptake. The SF
245 measurement can thus be considered as equal to the plant T (Gerdes et al., 1994).

246 During our experiment, five Dynagage SF sensors (Dynamax Inc, 2005) were used on each
247 (controlled stress and reference) field. The sensors were moved from one stem to another
248 every ten days. The objective was both to avoid damaging the monitored stems and to cover a
249 range of stem diameters. To upscale single-stem measurements to the field scale, the diameter
250 of each monitored stem as well as the actual distribution of diameter classes per m² was taken
251 into account. A stem density campaign (March 28th 2017) was carried out on both
252 experimental fields. An average density of 416 and 504 stems/m² was found on the controlled
253 stress and reference field, respectively. Five variability ranges in stem diameter were extracted
254 ([2.2;3.1], [3.1;3.7], [3.7;4.3], [4.3;4.8], [4.8;5.3] in mm) with a percentage contribution for
255 each interval of (6.8, 34.3, 20.5, 27.5, 10.9% respectively) for the controlled stress plot. For
256 the reference parcel, the five diameter intervals were ([2;3.4], [3.4;4.1], [4.1;4.8], [4.8;5.3],
257 [5.3;6.3] mm) with a percentage contribution for each interval of (26.4, 23.6, 37.5, 4.2, 8.3%
258 respectively). The mean (and standard deviation) of the diameter was estimated at 4.11 (0.68)
259 mm and 4.05 (0.78) mm for the controlled stress and reference fields, respectively.

260 Based on the stem variability ranges, the hourly field-scale SF-derived T is estimated as:

$$261 \quad T_{SF} = \sum_{i=1}^5 P_c(i) * T_{SF}(i) \quad (1)$$

262 where P_c(i) is the percentage of the diameter range i and T_{SF}(i) the T measured by a SF sensor
263 installed around a stem with diameter falling within the diameter range i (see appendix B).
264 Daily SF-derived T estimates are obtained by summing the hourly scaled SF-derived T. Note
265 that the data for days when more than one-third of SF measurements are missing (or invalid)
266 are removed (25 % of the data). Based on the same approach, the variability in T
267 measurements can be assessed by computing the weighted standard deviation of individual T
268 estimates:

$$269 \quad \sigma_{T_{SF}} = \sqrt{\frac{1}{4} \sum_{i=1}^5 P_c(i) * (T_{SF}(i) - T_{SF})^2} \quad (2)$$

270

271 2.5 Ancillary data

272 Other auxiliary measurements were carried out during the experiment. LAI measurements
 273 were made on a regular basis using hemispheric photos combined with biomass
 274 measurements. Cubic interpolation was used to obtain a daily estimate of LAI over the entire
 275 season. In addition, the Normalized Difference Vegetation Index (NDVI) was measured by a
 276 SKYE reflectometer installed over the controlled stress field. For the reference field, given
 277 that no NDVI sensor was available, NDVI was derived by combining the photo-derived LAI
 278 and a NDVI-LAI relationship developed for wheat in Er-Raki et al. (2007). The fractional
 279 vegetation cover (f_c) was derived by normalizing the NDVI by its minimum and maximum
 280 values obtained during the season. Also, in the rest of the paper we will use the normalized
 281 soil surface moisture (NSSM), which is derived from the surface (5-cm) soil moisture (SSM)
 282 normalized by its minimum and maximum values observed during the field experiment.

283 2.6 FAO dual crop coefficient (FAO-2Kc) approach

284 In FAO-2Kc, the crop ET is expressed as:

$$285 \quad ET_c = (K_{cb} + K_e) * ET_0 \quad (3)$$

286 where ET_c is the FAO-simulated potential ET, $K_e * ET_0$ the E component and K_{cb} the basal
 287 crop coefficient. The coefficient ($K_{cb} + K_e$) represents the ratio of ET_{FAO} to ET_0 under well-
 288 watered conditions (no vegetation stress). For actual estimates of the real crop ET (ET_{FAO}),
 289 K_{cb} is adjusted by the water stress coefficient K_s :

$$290 \quad ET_{FAO} = (K_{cb} \cdot K_s + K_e) * ET_0 \quad (4)$$

291 where ET_{FAO} is the FAO-simulated daily ET, $K_s < 1$ for conditions when the soil water is a
 292 limiting factor, and $K_s = 1$ when the root-zone soil water is easily available to T. Therefore, all
 293 three parameters K_{cb} , K_e and K_s are needed to estimate ET. The main equations of the FAO-
 294 2Kc approach are reminded in Appendix C.

295 The need for local calibration of the FAO model has been stressed by a number of studies (Er-
 296 Raki et al., 2007; 2011; Le Page et al., 2014). Herein, FAO-2Kc is calibrated by adjusting its
 297 ten main parameters:

- 298 - the length (L , number of days after sowing) of the initial (L_{ini}), development (L_{dev}), mid-
 299 season (L_{mid}) and late (L_{end}) phenological phase,
- 300 - the basal crop coefficient (K_{cb} , unitless) that is interpolated at the daily scale between the
 301 start and end value ($K_{cb,ini}$, $K_{cb,mid}$, $K_{cb,end}$) of each phenological phase,
- 302 - the depth (Z_e , mm) of surface soil layer subjected to drying by evaporation,
- 303 - the maximum depth of water (REW, mm) that can be evaporated without restriction from the
 304 soil surface layer, and
- 305 - the maximum rooting depth ($Z_{r,max}$, m).

306 Each parameter is adjusted separately by setting all the other parameters to their default
 307 (FAO) value and by maximizing the determination coefficient i) between modeled and EC-
 308 derived ET estimates and ii) between modeled and SF-derived T estimates. Interestingly
 309 enough, the maximum of correlation for ET and T estimates was found to occur
 310 simultaneously for the same set of parameter values.

311 Calibrated parameters are listed in Table 1. They are rather close for both experimental fields,
 312 but they significantly differ from the FAO default values, especially for the duration of
 313 phenological phases. Note however that the calibrated L_{ini} , L_{dev} and L_{mid} are in accordance
 314 with the NDVI measurements carried out on the site. Also, the site-specific Z_e and $Z_{r,max}$
 315 values may be due to the soil type, which is characterized by a clay and sand fraction of
 316 32.5% and 37.5%, respectively. Calibrated values of $Z_{r,max}$ and $K_{cb,mid}$ are 0.55 m and 0.95
 317 respectively, consistent with other fields in the region (Er-Raki et al., 2007, Belaqziz et al.,
 318 2013).

319 Table 1: Default (FAO) and site-specific FAO-2Kc parameters for controlled stress and
 320 reference fields separately.

Parameter	FAO	Controlled stress	Reference
$K_{cb,ini}$ (-)	0.15*	0.30*	0.30*
$K_{cb,mid}$ (-)	0.90	0.95	0.95
$K_{cb,late}$ (-)	0.23	0.15	0.15
L_{ini}	31	31	31
L_{dev}	34	34	40
L_{mid}	59	65	66
L_{late}	46	40	33
Z_e (m)	0.10	0.10	0.10
REW (mm)	9	8	8
$Z_{r,max}$ (m)	0.90	0.55	0.55

321 * $K_{cb,ini}$ is set to zero for NDVI~0.14 (bare soil) and a linear interpolation of $K_{cb,ini}$ is
 322 performed from the plant emergence until the last day of the initial phase where $K_{cb,ini}$ is set to
 323 0.15 (default) or 0.30 (value obtained after calibration).

324 The calibration approach is evaluated by comparing error statistics before and after
 325 calibration. For the controlled stress field, on one hand the coefficient of determination (R^2)
 326 between the simulated and observed ET flux increases from 0.70 to 0.75. The root mean
 327 square difference (RMSD) slightly varies from 0.72 to 0.75 mm/day and the mean difference
 328 (MD) from -0.03 to -0.05 mm/day. On the other hand, the R^2 increases significantly from 0.48

329 to 0.63 between the simulated and measured T, while the RMSD (MD) slightly varies from
 330 0.62 to 0.66 mm/day (from -0.89 to -0.99 mm/day). For the reference field, the R^2 between
 331 simulated and measured fluxes increases from 0.25 to 0.38 and from 0.78 to 0.81 for the T
 332 and ET estimates, respectively. The RMSD (MD) slightly changes from 0.64 to 0.83 mm/day
 333 (from -0.68 to -1.15 mm/day) and from 0.66 to 0.83 mm/day (from 0.36 to 0.27 mm/day) for
 334 the T and ET case, respectively. Overall, calibration results are fully consistent with the local
 335 calibration undertaken by Er-Raki et al. (2007) over 3 distinct wheat crop fields over the same
 336 study area yielding a RMSD with EC-derived ET of 0.45, 0.99, 0.75 mm/day.

337 2.7 Uncertainty analysis

338 The strategy to inter-compare EC, Lys, SF and FAO flux estimates and to assess uncertainties
 339 in E/T/ET estimates is presented. Given that it is difficult to rely on any measurement or
 340 modeling approach as an absolute reference for estimating the E/T partitioning, a new
 341 approach is proposed to estimate the systematic and random uncertainties in FAO, EC, Lys
 342 and SF methods. Herein, systematic uncertainty is defined as a persistent error that lasts for
 343 one week or more, while random uncertainty is defined as a relative error (error in the flux
 344 relative to the flux amplitude) that remains at the daily scale after removing systematic
 345 uncertainty.

346 For the systematic uncertainty analysis, as FAO-2Kc provides E, T and ET estimates, the
 347 FAO model is used for practical reasons as a common denominator in the inter-comparison of
 348 all approaches. The point is that the FAO model cannot be used as a reference for evaluating
 349 measurements. Therefore, any persistent difference between methods may be interpreted as a
 350 systematic error in the FAO and/or the measurement method.

351 For the random uncertainty analysis, the FAO model is also used as a common denominator in
 352 the inter-comparison of measurement methods but, since the FAO is generally more uncertain
 353 than observations, any systematic difference between FAO and measurements is removed at
 354 the 7-day scale. Specifically, the flux modeled by the FAO approach is corrected by making
 355 the difference between both 7-day smoothed estimates:

$$356 F_{FAO,Obs} = F_{FAO} - F_{FAO,Roll} + F_{Obs,Roll} \quad (5)$$

357 with F being the estimated (either ET, T or E) flux, F_{FAO} the FAO-simulated flux, $F_{FAO,Obs}$ the
 358 flux simulated by FAO model and corrected by the 7-day smoothed observed flux, $F_{FAO,Roll}$
 359 the 7-day smoothed FAO-simulated flux and $F_{Obs,Roll}$ the 7-day smoothed observed flux. Note
 360 that the observed flux is derived by either EC and Lys or SF data or any combination between
 361 them. Equation (5) means that only the (short-term) day-to-day variations of the FAO-
 362 simulated fluxes are kept for the inter-comparison of the random uncertainty in measurement
 363 methods. The risk is thus limited as 1) systematic errors in FAO model have been removed
 364 and 2) the FAO model is very well constrained at the daily scale by the well monitored
 365 irrigation and ET_0 input data.

366 Finally, an estimate of the random uncertainty in the T/ET ratio, noted $\delta(T/ET)/(\overline{T/ET})$, can
 367 be estimated by taking the derivative of the logarithm of each term:

368
$$\frac{\delta(T/ET)}{T/ET} = \frac{\delta T}{\bar{T}} + \frac{\delta ET}{\overline{ET}}$$
 (6)

369 with δT being the standard deviation between corrected FAO-simulated and measured T, \bar{T}
370 the mean measured T during the study period, δET the standard deviation between corrected
371 FAO-simulated and measured ET and \overline{ET} the mean measured ET during the study period.
372 Note that Equation (6) is valid if variables are exempt from systematic uncertainties.

373 **3. Results and discussion**

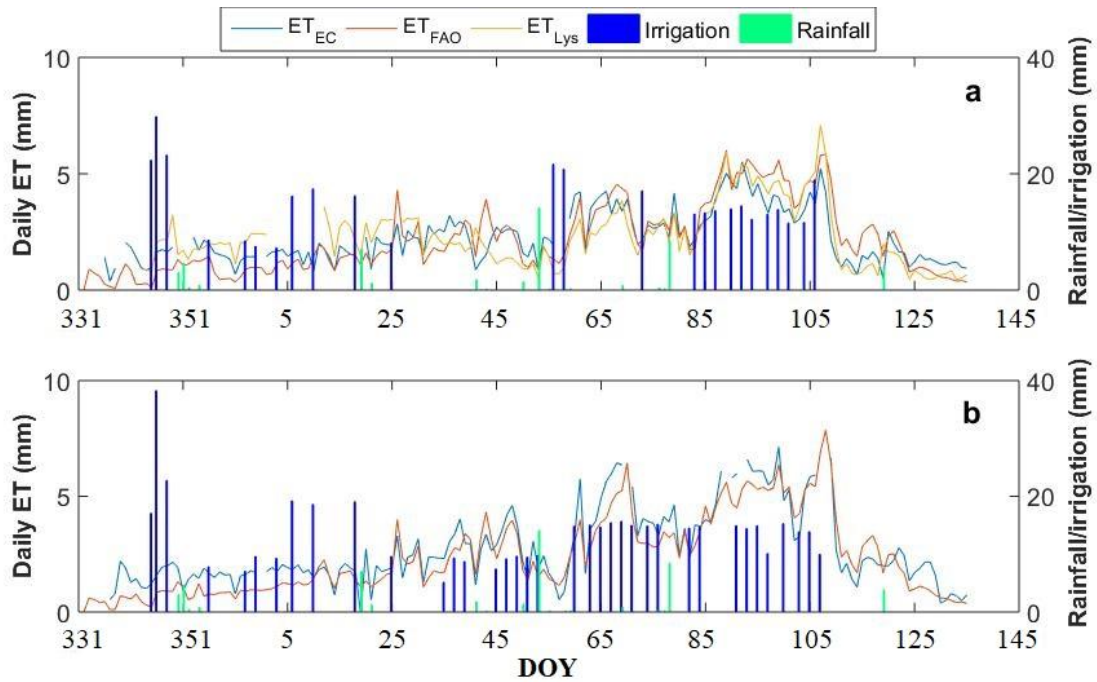
374 All methods (FAO-2Kc, EC, Lys, SF) are inter-compared to evaluate both systematic and
375 random uncertainties in E, T and ET estimates over both (controlled stress and reference) crop
376 fields. The dynamics of a best estimator of the partitioning ratio is then analyzed at the daily
377 to seasonal time scales in response to several environmental and biophysical factors such as
378 LAI, NSSM and vapor pressure deficit (VPD).

379 3.1 Systematic differences between ET, T and E methods

380 *3.1.1 Evapotranspiration*

381 Figure 3 shows the daily evolution of EC-derived and Lys-derived ET along with the amount
382 of precipitation and irrigation for the controlled stress and reference fields separately. One can
383 see the general coherence between FAO, EC and Lys estimates across all phenological phases.
384 When comparing both experimental fields, Figure 3 shows that the ET measured by EC is
385 significantly larger for the reference than for the controlled stress field. This is expected
386 because the reference field did not experience water stress as previously mentioned. In
387 particular, the daily ET reaches 7.1 mm at reference field against a maximum value of 5.4 mm
388 on the same date at controlled stress field. This effect is notably visible between Day Of Year
389 (DOY) 65 and DOY 85, when the ET at controlled stress field is 1 mm to 3 mm less than that
390 at reference field, due to the water supply shortage over the controlled stress field.

391 When comparing ET methods over the controlled stressed field (Figure 3a), slight differences
392 between EC- and Lys-derived ET could be attributed to a lack of representativeness of the
393 conditions inside the Lys. However, representativeness issues are limited by the regulation of
394 the soil water tension at the SFL Lys bottom.

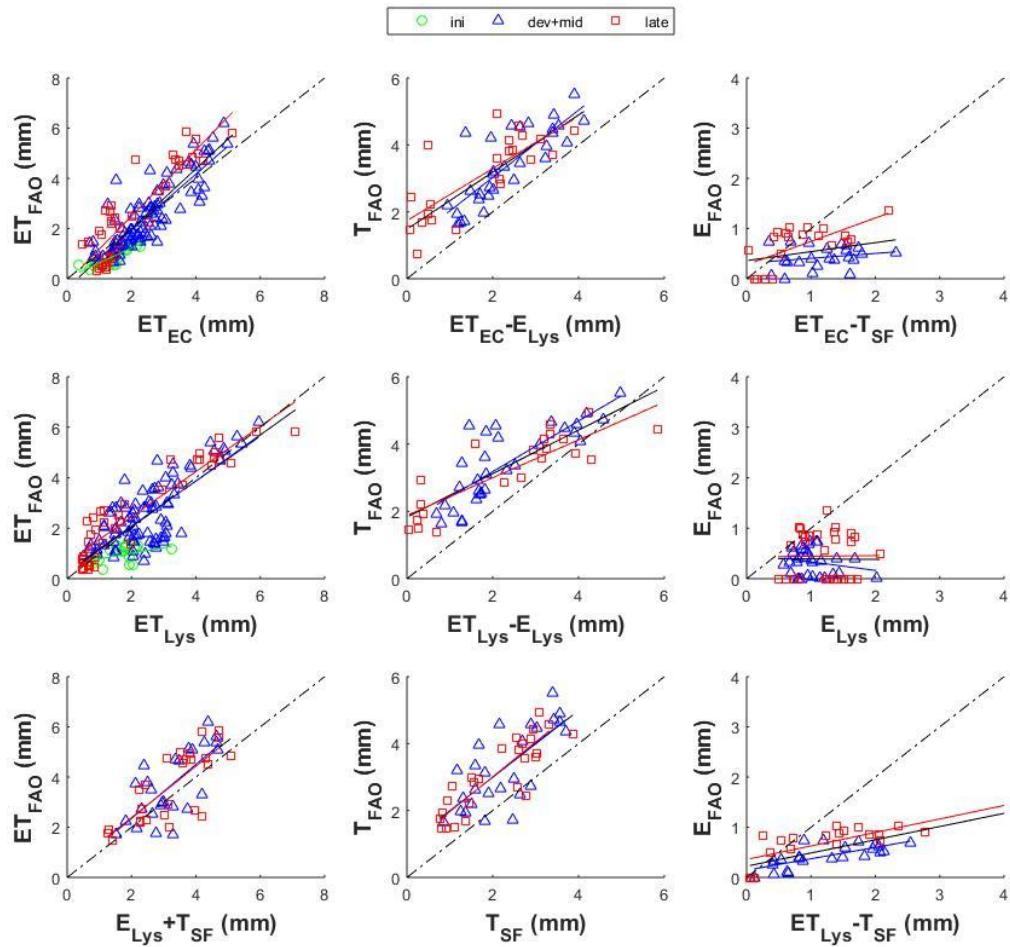


395

396 Figure 3: Time series of EC-derived, Lys-derived and FAO-simulated daily ET at the
 397 controlled stress (a) and reference (b) field.

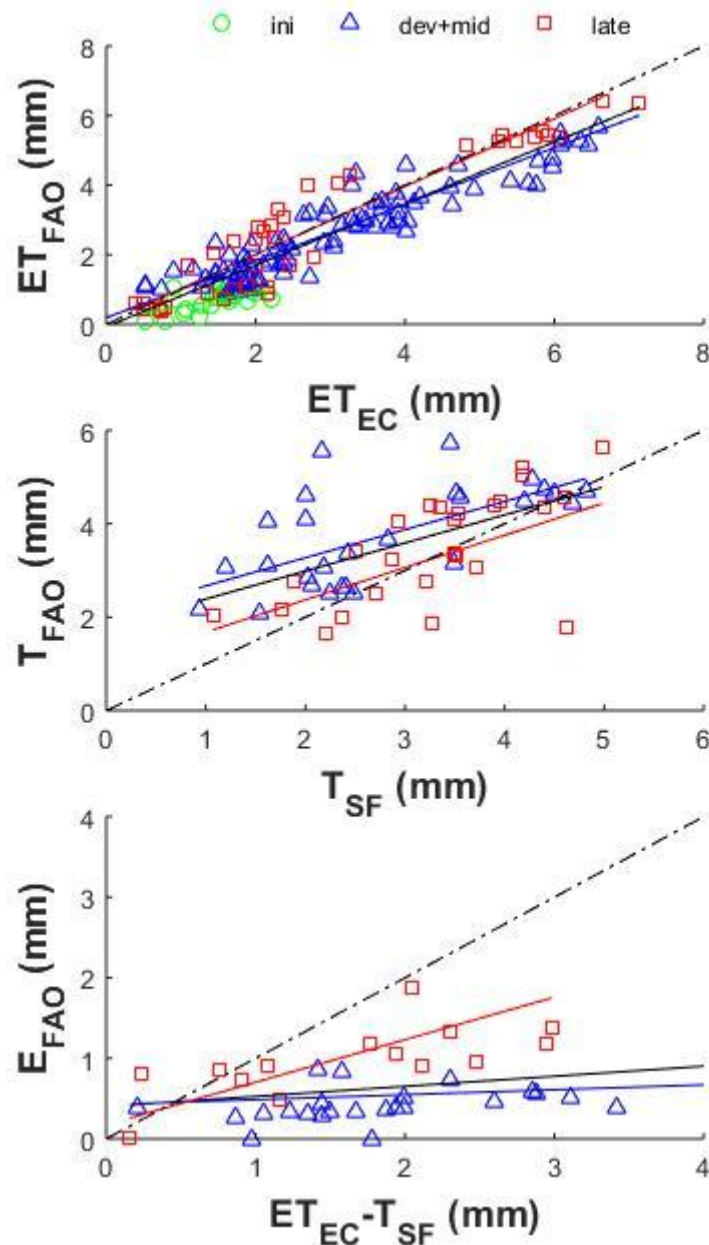
398 In fact, despite the huge discrepancy existing between the spatial extent of both ET
 399 techniques, EC- and Lys-derived ET estimates are deemed consistent as differences between
 400 those independent measurements remain relatively low (with an overall RMSD of 0.73
 401 mm/day). The EC-derived ET matches much better the Lysimeter-derived ET with Bowen
 402 correction than without correction (with an overall RMSD of 1.14 mm/day).

403 When comparing the FAO model with the other two ET methods (EC and Lys) in Figure 4
 404 and 5, it appears that the modeled flux is systematically lower than both the Lys- and EC-
 405 derived ET during the initial stage. Associated statistical results are listed in Table 2. The
 406 slope of the initial period ($a_{ini}=0.40$) is much lower than that of both development and mid-
 407 season ($a_{dev+mid}=0.82$) and late ($a_{late}=0.98$) periods. The systematic underestimation of the
 408 FAO model during the initial stage is probably due to an underestimation of the E flux. Such
 409 an assumption will be further assessed below by investigating independent T and E estimates.



410

411 Figure 4: Scatterplot of FAO-simulated versus measured ET/T/E fluxes over the controlled
 412 stress field.



413

414

Figure 5: Same as Figure 4, but for the reference field.

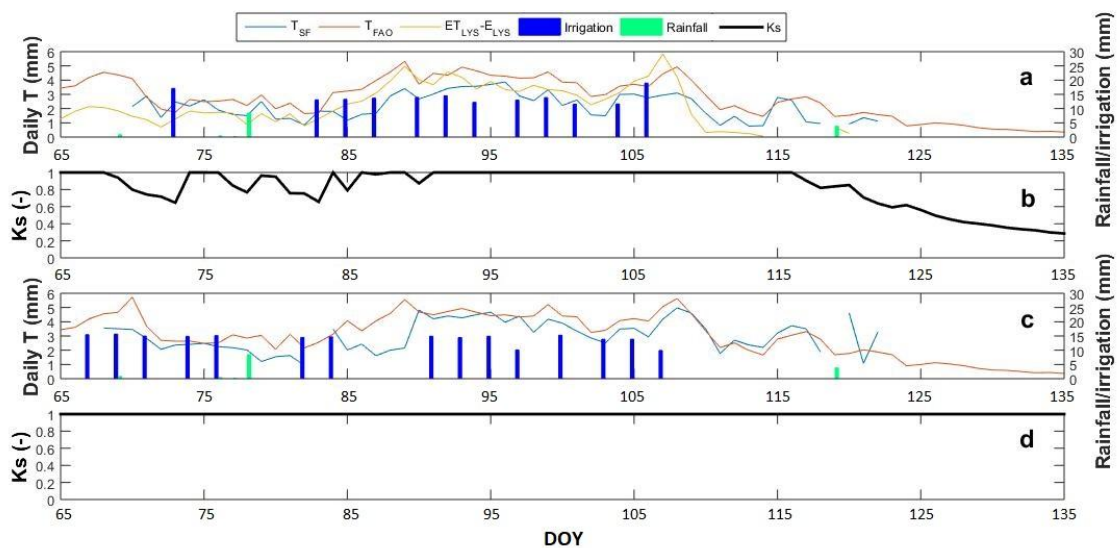
415 *3.1.2 Transpiration*

416 Four different methods are assessed to estimate the T component: FAO-2Kc model, SF
 417 sensors (T_{SF}), the combination ($ET_{Lys} - E_{Lys}$) of both Lys set up over transpiring (ET_{Lys}) and
 418 non-transpiring (E_{Lys}) wheat, and the combination ($ET_{EC} - E_{Lys}$) between EC and Lys. It is
 419 reminded that the FAO-2Kc and SF techniques are implemented over both (controlled stress
 420 and reference) experimental fields, while the two Lys operate in the controlled stress
 421 only.

422 Figures 4 and 5 present the scatterplots of FAO-simulated versus observed (SF- and Lys-
 423 derived) T while Figures 6a and 6c show the temporal evolution of T estimates from DOY 65

424 to DOY 135 over the controlled stress and reference field, respectively. All three independent
 425 estimates are generally consistent. At first order, the dynamics of T follow the atmospheric
 426 demand on a day-to-day basis. It also increases with both the irrigation frequency and wheat
 427 development until DOY 107 when senescence starts. Note that SF-derived and FAO-
 428 simulated T are very close from DOY 90 to DOY 118 over the reference field (Figure 6c). All
 429 three T methods consistently provide generally higher T values in the reference field than in
 430 the controlled stress field, with a maximum T of 5.6 (5.0) mm and 5.2 (4.1) mm for the FAO
 431 model (SF method), respectively. Note that the large peak in Lys data reaching 5.8 mm on
 432 DOY 107 over the controlled stress field is probably attributed to wetter conditions inside the
 433 Lys than outside on that particular wet date.

434 The SF-derived T estimates of both fields are of similar amplitude before DOY 85 (see Figure
 435 6a and 6c) despite the irrigation water shortage from DOY 65 to DOY 85 at the controlled
 436 stress field. This may be due to the relatively low climatic demand during that period while
 437 the soil water content was very different between the two plots. After DOY 85, the SF-derived
 438 T of the reference field is clearly superior to that of the controlled stress field. In fact, the
 439 impact of water deficit on wheat T is highly dependent on the atmospheric evaporative
 440 demand.



441
 442 Figure 6: Time series of FAO-simulated, Lys-, SF-derived T and stress coefficient (Ks) over
 443 the controlled stress (a, b) and reference (c, d) field.

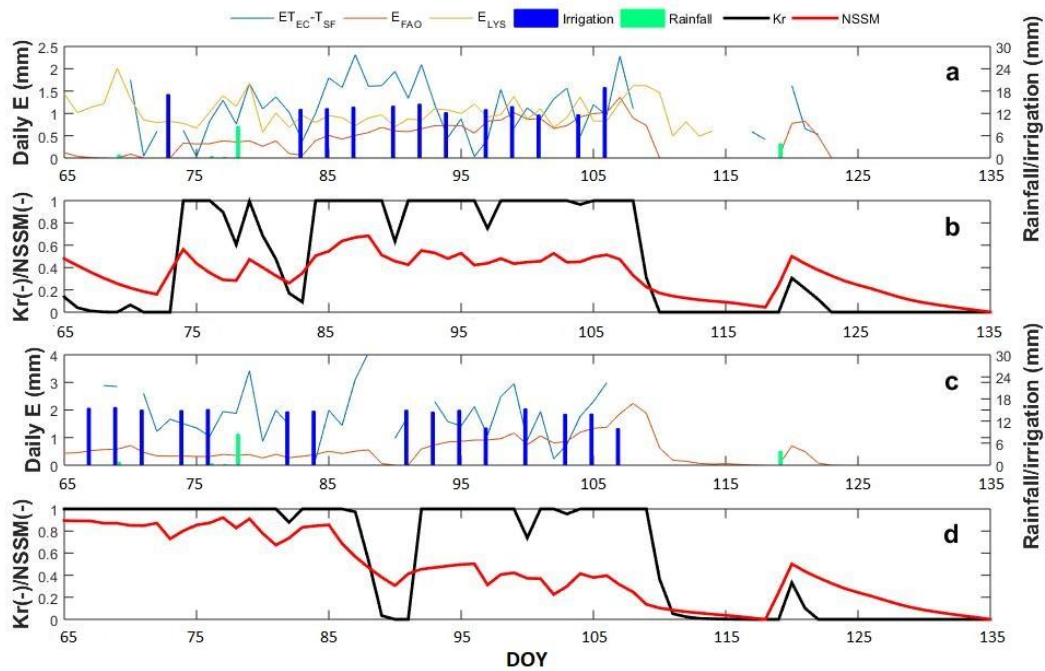
444 Over the controlled stress field, the difference between the Lys- and SF-derived T is rather
 445 variable. Lys tends to overestimate SF-derived T in wet conditions and underestimate SF-
 446 derived T in dry conditions, similarly to the EC/Lys comparison in the ET case described
 447 previously. However, when comparing all three approaches (FAO, SF and Lys), SF-derived T
 448 is generally lower than both FAO and Lys estimates during the crop development. This effect
 449 is more visible for the controlled stress field than for the reference field where FAO and SF
 450 methods match relatively well (except from DOY 85 to DOY 90). The slight underestimation
 451 of SF-derived T could be attributed to issues in the up-scaling technique from the 3-5
 452 monitored stems to the field scale.

453 Table 2 lists the statistical results between modeled and measured T for the controlled stress
454 and reference fields separately. The MD between FAO-simulated and Lys-, SF-, and EC-Lys-
455 derived T is -1.01, -0.99, and -1.17 mm, respectively. The T modeled by FAO-2Kc is
456 generally larger than that of all three methods: SF, Lys-only and EC and Lys combined (ET_{EC} -
457 E_{Lys}). The overestimation of the model is clearly seen in the scatterplots of Figure 4
458 (controlled stress field). Such phenomenon is also observed on the reference field (Figure 5)
459 although the difference between FAO-simulated and SF-derived T is smaller between DOY
460 90 and DOY 110, when the vegetation was fully covering the soil (as opposed to the
461 controlled stress field) so that E was minimized by the vegetation screening effect. Given that
462 the FAO model has not a significant bias on ET estimates during the development stage, a
463 direct consequence of the overestimation of T by the FAO model is its underestimation of E.
464 This result is fully consistent with the systematic underestimation of ET by FAO-2Kc during
465 the initial stage (see previous discussion about ET estimates).

466 3.1.3 Evaporation

467 Figures 4 and 5 present the scatterplots of FAO-simulated versus observed (Lys- and EC/SF-
468 derived) E while Figures 7a and 7b shows the temporal evolution of E estimates from DOY
469 65 to DOY 135 for the controlled stress and reference field, respectively. The model
470 underestimates E, especially during relatively dry periods. This result is consistent with
471 previous discussions on 1) the underestimation of ET by the FAO model during the initial
472 period (when E is dominant) and 2) the overestimation of T (at the expense of E) during the
473 crop development period. However, the underestimation of E by FAO-2Kc can be
474 compensated by an overestimation of T, thus providing quite satisfying results in terms of ET
475 estimates, especially during the crop development period. This result is consistent with that
476 obtained by Er-Raki et al. (2007) on wheat crop, for flood-irrigation, under semi-arid climate.

477 Very low slopes (in the range -0.2-0.2 during the development phase) of the linear regression
478 between modeled and observed E are reported in Table 2. The generally poor correlation
479 between modeled and observed E is notably due to a much faster drying of the SSM in the
480 FAO model than in the Lys (Pruitt and Lourence, 1985; Allen et al., 2011). The FAO-
481 simulated E drops quickly (and at an earlier stage than Lys mass) after an irrigation event and
482 neglects E in relatively dry conditions during which Lys measures a minimum E rate of 0.5
483 mm per day (see Figure 7a). Interestingly enough, the FAO-simulated E is getting closer to
484 the Lys-derived estimate during the wettest period from DOY 85 to DOY 105. In dry
485 conditions (for NSSM <0.4), the FAO-simulated E is generally estimated as 0, regardless of
486 the remaining soil water availability (see Figure 5 for E) although the 100% vegetation
487 coverage was never reached on this field during the experiment. It is suggested that the FAO
488 formalism is not able to simulate E accurately in the full SSM range (Allen et al., 2011;
489 Gharsallah et al., 2013). Note that the same results were obtained in Er-Raki et al. (2007) and
490 Saadi et al. (2015) for irrigated and rainfed cereals under semi-arid climate.



491

492 Figure 7: Time series of FAO-simulated and EC/SF-derived and Lys-derived E, E reduction
 493 coefficient (Kr) and NSSM over the controlled stress (a, b) and reference (c, d) field.

494 EC/SF-derived E is not stable and varies rapidly on both controlled stress (Figure 7a) and
 495 reference (Figure 7c) fields. Although the mean E values obtained by Lys and EC/SF methods
 496 are similar (and consistently larger than the mean FAO-simulated E), large differences
 497 between Lys- and EC/SF-derived daily estimates are visible in Figure 7a all along the study
 498 period. Indeed, the combination of EC and SF data is likely to increase the uncertainty in E
 499 estimates because two independent measurements are used (with their respective spatial extent
 500 and uncertainty) and because E is significantly smaller than ET and T during the development
 501 phase.

502 3.2 Random uncertainties in ET, T and E estimates

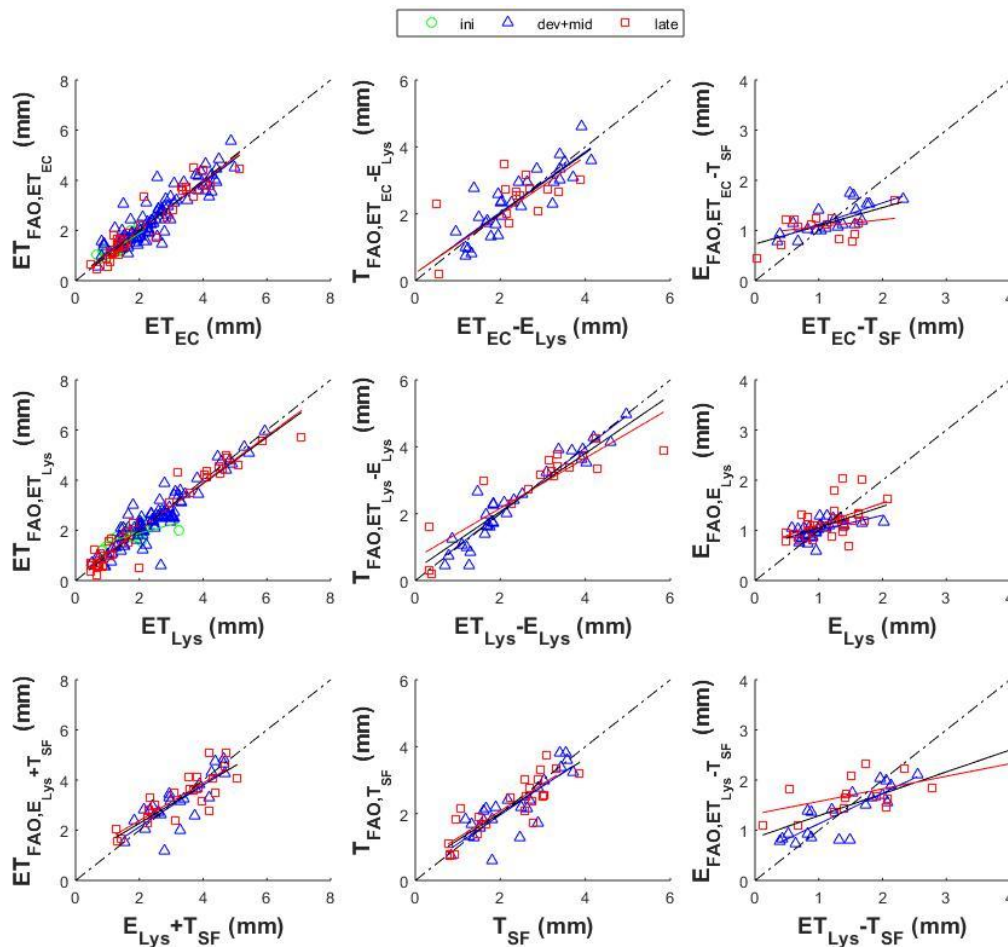
503 3.2.1 Controlled stress field

504 The main impact of the correction using Equation (6) is evident with a MD close to zero in all
 505 cases (Table 2). In particular, the underestimation of ET by FAO model during the initial
 506 period no longer appears (Figure 8). Similarly, the overestimation of T by FAO model during
 507 the development period is reduced to approximately zero. Meanwhile, the correlation of
 508 $F_{FAO,Obs}$ (derived from Equation 6) vs F_{Obs} is systematically closer to 1 than the correlation of
 509 $F_{Obs,roll}$ vs F_{Obs} . More interesting are the relative magnitudes of R^2 for each measurement
 510 method and the magnitude of the changes in R^2 before and after correction. In terms of ET
 511 notably, the highest R^2 without correcting FAO estimates is attributed to EC (0.74 in Table 2)
 512 while the highest R^2 with the correction is attributed to Lys (0.89 in Table 2). In terms of T,
 513 the highest R^2 is attributed to Lys without (0.67 in Table 2) and with (0.85 in Table 2) the
 514 correction. By considering that the relative magnitude of R^2 is an indicator of the relative
 515 random uncertainty in measurement methods, Lys represents the most precise method for

516 estimating ET and T. The Lys method actually relies on a direct measure of the water weight,
 517 which is very precisely estimated. Moreover, both Lys and the FAO-2Kc model are based on
 518 the water balance, which may also explain this relatively low uncertainty of Lys data
 519 compared to corrected FAO-simulated flux estimates.

520 Regarding the E term, analysis is more complex as the FAO model is found to be poorly
 521 correlated with both Lys and EC/SF measurements, due to 1) a too fast drying of the top soil
 522 layer in the FAO modeling and 2) long periods with modeled E set to zero. Therefore, the
 523 assumption (i.e. linearity of possible biases in FAO flux estimates) on which the correction
 524 approach is based is invalid for E. Although Equation (13) is still applied to E as a first guess
 525 estimate of the relative random uncertainty in Lys and EC/SF measurements, one bears in
 526 mind that the corrected FAO-simulated E is unlikely to provide a robust reference for
 527 comparison purposes.

528 As a step further, the standard deviation between corrected FAO-simulated and measured
 529 fluxes is computed in all cases to estimate the relative random uncertainty of each method and
 530 for each flux (ET, T and E) separately. The relative random uncertainty in ET is 10%, 7.6%
 531 and 12% for EC, Lys and Lys/SF respectively. The estimated uncertainty in T is 15%, 12%
 532 and 17% for SF, Lys and EC/Lys, and the estimated uncertainty in E is 18%, 29% and 24%
 533 for Lys, EC/SF and Lys/SF, respectively.

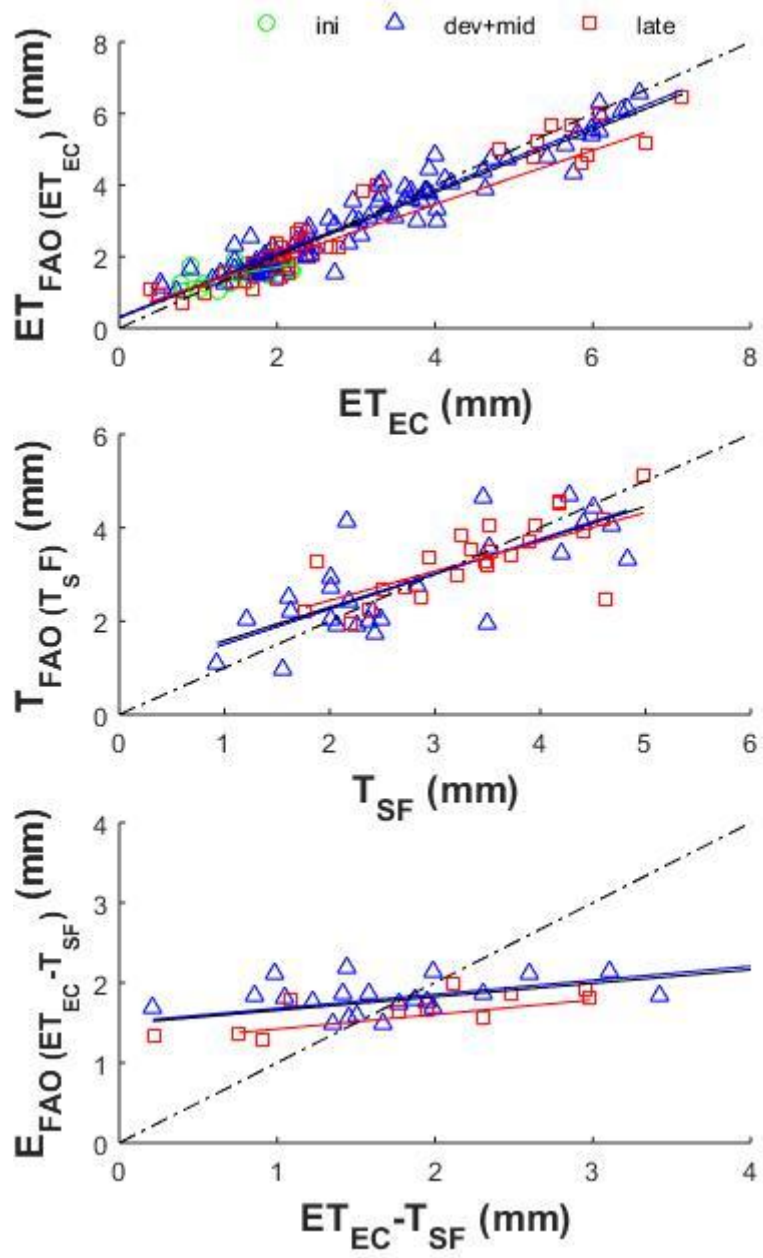


534

535 Figure 8: Scatterplot of corrected FAO-simulated versus measured fluxes over the controlled
536 stress field.

537 *3.2.2 Reference field*

538 Figure 9 presents the scatterplots between corrected FAO-simulated and measured ET, T and
539 E separately. Results are similar to those obtained previously for the controlled stress field.
540 The R^2 is 0.92 (0.86) for ET, 0.59 (0.71) for T and 0.33 (0.44) for E over the reference
541 (controlled stress) field, respectively (Table 2). The higher scatter of T estimates is attributed
542 to the first part of the development period (from DOY 65 to DOY 90) when the daily
543 difference between corrected FAO-simulated and SF-derived T is significant. Results in terms
544 of E estimates are also quite consistent for both fields, with a generally low sensitivity of the
545 FAO model to variations in E measurements, implying a low R^2 between corrected FAO-
546 simulated and EC-SF measured E. The relative random uncertainty is 8.3%, 14% and 33% for
547 EC-derived ET, SF-derived T and EC/SF-derived E, respectively.



548

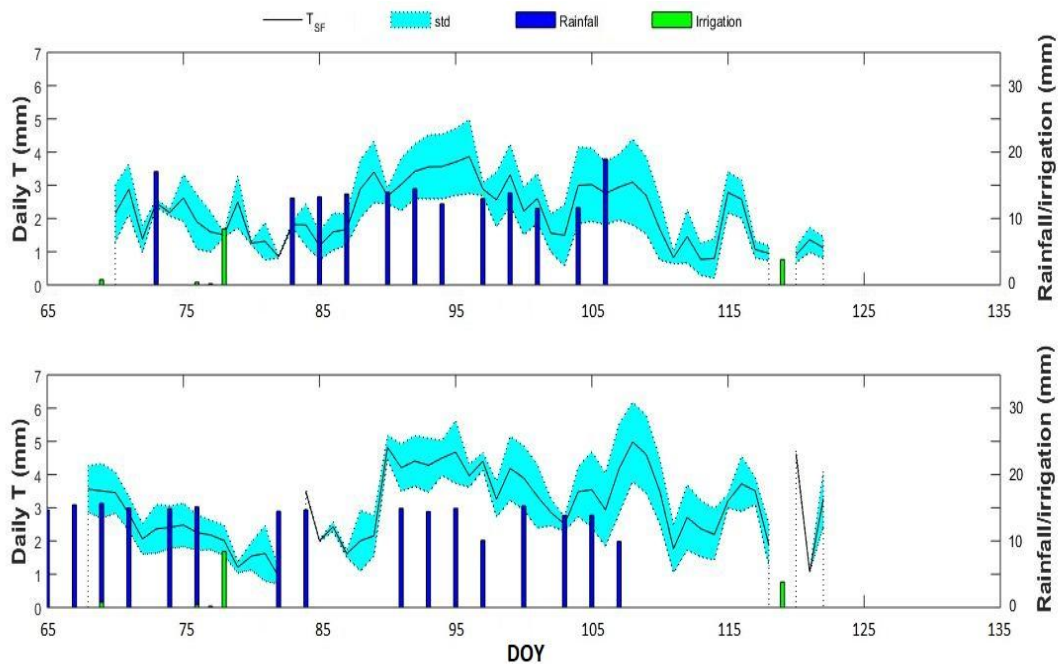
549 Figure 9: Scatterplot of corrected FAO-simulated versus measured fluxes over the reference
 550 field.

551 Table 2: Statistical results in terms of determination coefficient (R^2), root mean square difference (RMSD), mean difference (MD), slope and intercept
552 of the linear regression between FAO-simulated and measured fluxes before and after correction over the controlled stress and reference field.

Field	Correction	Flux	Method	R^2				RMSD (mm)				MD (mm)				Slope				Intercept (mm)			
				All	ini	dev+mid	late	All	ini	dev+mid	late	All	ini	dev+mid	late	All	ini	dev+mid	late	All	ini	dev+mid	late
Controlled stress	No	ET	ET _{EC}	0.75	0.68	0.74	0.80	0.75	0.23	0.51	0.49	-0.05	0.55	0.01	-0.51	1.19	0.59	1.12	1.32	-0.38	0.04	-0.30	-0.14
			ET _{Lys}	0.66	0.13	0.55	0.86	0.82	0.33	0.64	0.39	-0.03	0.81	-0.03	-0.44	0.91	0.22	0.89	0.90	0.23	0.56	0.30	0.66
			E _{Lys} +T _{SF}	0.55	-	0.52	0.58	0.55	-	0.40	0.38	-0.41	-	-0.44	-0.41	1.02	-	1.08	1.03	0.33	-	0.19	0.31
		T	T _{SF}	0.63	-	0.53	0.74	0.66	-	0.50	0.44	-0.99	-	-1.00	-1.01	1.00	-	1.01	1.04	1.00	-	0.97	0.92
			ET _{Lys} -E _{Lys}	0.67	-	0.66	0.73	0.72	-	0.56	0.43	-1.01	-	-1.11	-0.86	0.65	-	0.75	0.56	1.83	-	1.68	1.88
			ET _{EC} -E _{Lys}	0.62	-	0.66	0.60	0.77	-	0.52	0.55	-1.17	-	-1.03	-1.36	0.85	-	1.00	0.78	1.48	-	1.02	1.73
		E	E _{Lys}	0.00	-	0.04	0.00	0.54	-	0.34	0.41	0.71	-	0.68	0.74	-0.01	-	-0.17	0.01	0.40	-	0.50	0.43
			ET _{EC} -T _{SF}	0.09	-	0.05	0.43	0.37	-	0.34	0.15	0.48	-	0.76	0.19	0.18	-	0.10	0.47	0.36	-	0.31	0.28
			ET _{Lys} -T _{SF}	0.50	-	0.52	0.61	0.50	-	0.36	0.34	0.72	-	0.81	0.65	0.26	-	0.23	0.27	0.22	-	0.14	0.36
	Yes	ET	ET _{EC}	0.86	0.78	0.81	0.90	0.39	0.07	0.34	0.18	-0.01	0.00	-0.01	-0.01	0.95	0.79	0.93	0.98	0.13	0.30	0.18	0.06
			ET _{Lys}	0.89	0.43	0.85	0.94	0.40	0.14	0.31	0.22	0.01	-0.01	0.02	0.00	0.92	0.34	0.94	0.94	0.17	1.20	0.13	0.15
			E _{Lys} +T _{SF}	0.67	-	0.65	0.70	0.32	-	0.22	0.22	0.01	-	0.07	-0.09	0.76	-	0.83	0.75	0.75	-	0.47	0.89
		T	T _{SF}	0.71	-	0.70	0.72	0.26	-	0.19	0.17	0.02	-	0.08	-0.06	0.81	-	0.86	0.81	0.39	-	0.24	0.47
			ET _{Lys} -E _{Lys}	0.85	-	0.91	0.79	0.28	-	0.15	0.23	0.00	-	-0.01	0.01	0.87	-	0.98	0.75	0.33	-	0.05	0.67
			ET _{EC} -E _{Lys}	0.70	-	0.74	0.63	0.31	-	0.21	0.24	0.00	-	-0.01	0.03	0.90	-	0.91	0.87	0.23	-	0.23	0.23
		E	E _{Lys}	0.31	-	0.29	0.28	0.18	-	0.11	0.15	0.00	-	-0.01	-0.01	0.42	-	0.30	0.43	0.64	-	0.71	0.68
			ET _{EC} -T _{SF}	0.44	-	0.57	0.10	0.18	-	0.12	0.13	0.00	-	0.01	0.03	0.36	-	0.43	0.14	0.73	-	0.70	0.94
			ET _{Lys} -T _{SF}	0.54	-	0.70	0.40	0.25	-	0.12	0.22	-0.01	-	0.01	0.00	0.44	-	0.61	0.25	0.85	-	0.52	1.32
Reference	No	ET	ET _{EC}	0.85	0.35	0.87	0.84	0.71	0.34	0.55	0.29	0.38	0.79	0.39	0.00	0.89	0.40	0.82	0.98	-0.07	0.10	0.19	0.05
		T	T _{SF}	0.34	-	0.44	0.38	0.64	-	0.55	0.32	-0.57	-	-0.89	-0.01	0.60	-	0.60	0.69	1.79	-	2.07	0.99
		E	ET _{EC} -T _{SF}	0.08	-	0.04	0.67	0.69	-	0.67	0.16	1.17	-	1.31	0.58	0.12	-	0.06	0.53	0.40	-	0.43	0.18
	Yes	ET	ET _{EC}	0.92	0.32	0.93	0.90	0.43	0.13	0.34	0.23	0.05	0.00	0.03	0.16	0.88	0.38	0.89	0.76	0.29	0.94	0.32	0.44
		T	T _{SF}	0.59	-	0.61	0.50	0.38	-	0.32	0.22	0.00	-	-0.02	0.03	0.72	-	0.75	0.63	0.86	-	0.76	1.19
		E	ET _{EC} -T _{SF}	0.33	-	0.35	0.84	0.33	-	0.31	0.12	0.01	-	-0.04	0.36	0.17	-	0.17	0.18	1.48	-	1.51	1.24

553 *3.2.3 Daily uncertainty in SF-derived T*

554 To further investigate the random uncertainty in SF measurements, a statistical analysis is
 555 undertaken at the daily time scale by exploiting the 3 to 5 SF sensors that were operating
 556 simultaneously over each crop field. In practice, the standard deviation of daily individual
 557 estimates is computed for each field. Figure 10 shows the evolution of the daily mean and
 558 standard deviation of SF-derived T for both experimental sites separately. The daily standard
 559 deviation generally increases with T and the variation of the standard deviation is greater on
 560 the stressed than on the reference plot. A relatively small standard deviation is visible in
 561 Figure 10 from DOY 65 to DOY 85. This duration is characterized by a lack of irrigation
 562 water as mentioned above. From DOY 85 to DOY 110, the standard deviation is larger. The
 563 increase in standard deviation between both periods can be explained by the impact of the
 564 water supply shortage, in addition to drip irrigation that wets only 30% of soil. The partial
 565 wetting of soil may involve differences in T between wheat stems depending on their position
 566 relative to the irrigation tube. On the contrary, the reference plot was well irrigated throughout
 567 the cultivation stages and allowed the wheat stems to maintain a good uniformity.



568
 569 Figure 10: Time series of the daily mean and standard deviation of SF-derived T over the
 570 controlled stress (top) and reference (bottom) field.

571 *3.3 T/ET ratio:*

572 Previous analyses about systematic and random uncertainties in ET, T and E estimates are
 573 used to quantify the relative accuracy in the partitioning ratio and to interpret its dynamics at
 574 the daily and seasonal time scales.

575 *3.3.1 Controlled stress field*

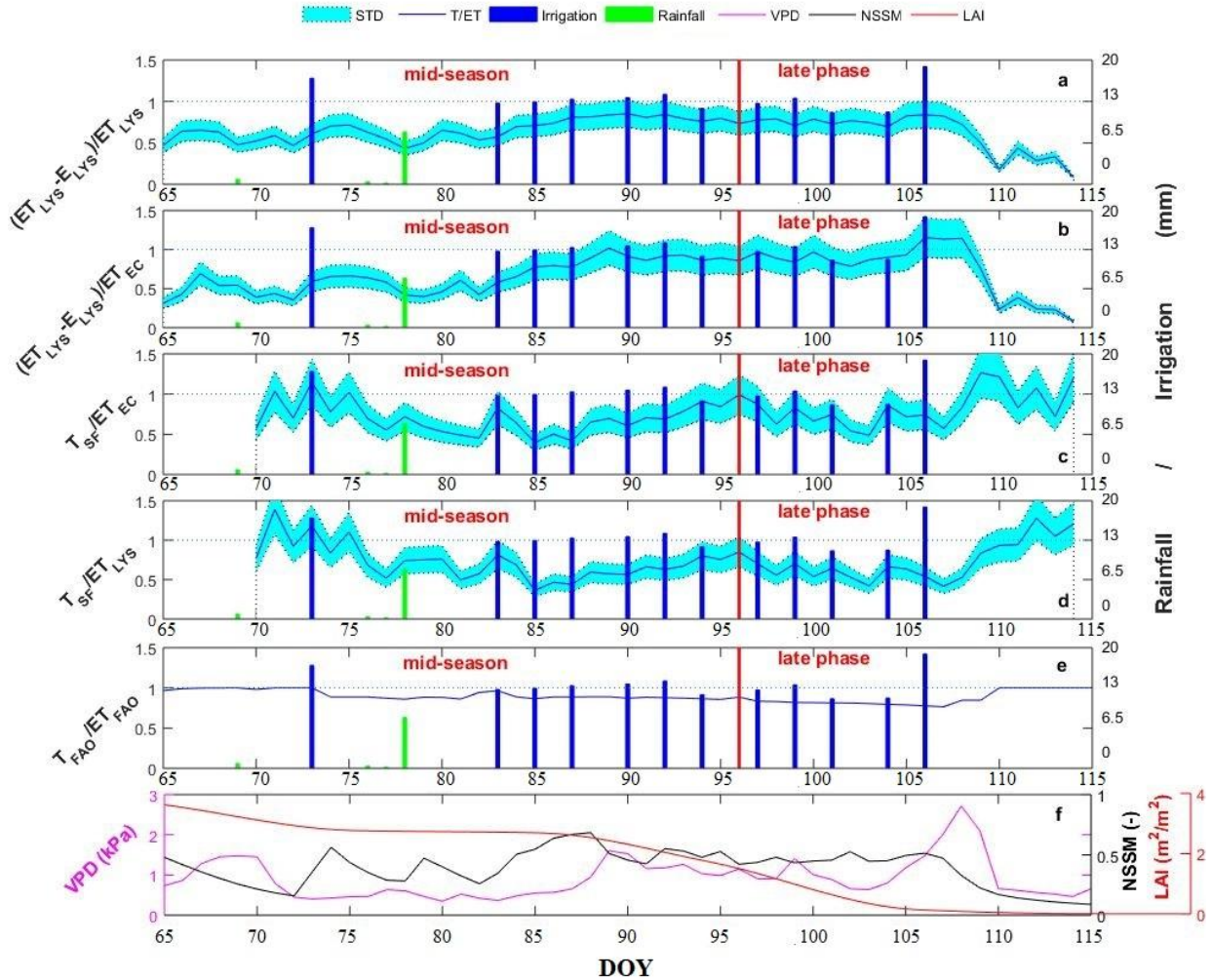
576 Figures 11a and 11b show the evolution of the T/ET ratios derived from Lys and Lys/EC data,
577 respectively from DOY 65 to 114. Both dynamics are fully consistent, given the strong
578 coherence between Lys- and EC-derived ET estimates. The T/ET value is about 0.5 at DOY
579 65, increases up to 0.8-0.9 before the end of the middle-season phase, then keeps a relatively
580 constant value until the beginning of senescence, and then suddenly drops to low values (0.10-
581 0.30) at about DOY 110. The increase of the partitioning ratio from DOY 65 to DOY 90 is
582 associated with an increase of the irrigation frequency. It seems that the portion of T increases
583 with the soil water availability. At the early stage of senescence, T decreases continually so
584 that the T/ET ratio gets low values regardless of the soil water availability and the green
585 fraction cover. Note that T/ET values larger than 1 are obtained on DOY 106-108 by
586 combining Lys and EC data. This is due principally to the overestimation of EC-derived ET
587 by the Lys technique in wet conditions. Nonetheless, both Lys- and Lys/EC-derived
588 partitioning ratios provide consistent and physically sound variations all along middle-
589 development and late phases.

590 Figures 11c and 11d plot the T/ET ratios derived from SF/EC and SF/Lys data, respectively.
591 Both cases show an irregularity at the beginning of the measurement period (DOY 70 to DOY
592 75) as well as during the senescence period (from DOY 109). The suspicious behavior of SF-
593 derived T from DOY 70 to DOY 75 is probably due to a loose contact between the SF sensors
594 and stems, which causes large fluctuations of the SF output. Indeed, the water stress
595 experienced by the controlled stress wheat may have caused a loss of tissue water, leading to a
596 decrease in the turgidity of the cells, and subsequently a decrease in the size of the stems and
597 hence in the quality of the contact with SF sensors. During senescence, another phenomenon
598 occurs when the SF-derived T exceeds both EC-derived and Lys-derived ET. Such erroneous
599 behavior of the T/ET ratio could be explained by the drying of wheat stems, resulting in a
600 drastic change in the energy dissipation through the stem. Note that the SF-derived T/ET is
601 generally difficult to interpret as the whole study period is characterized by unstable
602 variations, which may be attributed to upscaling issues of the SF-derived T measured at 3-5
603 individual wheat stems only.

604 Figure 11e presents the evolution of the T/ET ratio modeled by FAO-2Kc during the season
605 for the controlled stress field. This ratio varies between 0.86 and 1 and generally slightly
606 decreases after irrigation or rainfall. The model's response to the water inputs is expected as
607 the E component increases with the water availability in the soil surface. However, the FAO-
608 modeled T/ET is much too close to 1 compared to all measured estimates, especially during
609 relatively dry periods, the mid-season and the senescence phases. As discussed earlier, the
610 model clearly underestimates E compared to the field measurements made in this experiment.
611 This implies an over-estimation of the T/ET ratio, particularly after the cessation of irrigation
612 for a few days (e.g. before DOY 83 and after DOY 106).

613 The correlation coefficient (R) between the T/ET ratios and potential variability factors
614 (NSSM, LAI and VPD) are reported in Table 3. Since the SF-derived T is clearly unreliable
615 during the senescence period, all results are presented for both the entire partitioning period
616 and, in parentheses, the same period by excluding the senescence period. The largest R
617 (+0.82) is obtained for Lys-derived T/ET with NSSM. The variations of the partitioning ratio

618 derived from Lys data are thus easier to interpret from potential variability factors (such as
619 NSSM) than those of the other T/ET estimates. This is consistent with the previous
620 assessment of systematic and random uncertainties in measurement techniques, demonstrating
621 that Lys provides reasonable E/T estimates. However, the positive sign of the correlation
622 between Lys-derived T/ET and NSSM is unexpected as the E portion should increase with
623 SSM (Liu et al., 2002; Kang et al., 2003). In fact, our experiment was undertaken under semi-
624 arid conditions and after DOY 65, when the green LAI had already reached its maximum
625 value. It is hence suggested that, under such conditions, the SSM is a good proxy for the soil
626 water availability to T (instead of E). Consequently, the T portion increases with SSM while
627 the E underneath the wheat canopy is maintained at a relatively constant level. When looking
628 at SF-derived T/ET, a negative correlation is obtained with NSSM. The point is that this
629 correlation is significantly decreased (from -0.46 to -0.18) when excluding the senescence
630 period. Therefore, the statistical significance of this negative correlation is questionable. The
631 opposite sign of the correlations obtained for SF-derived and Lys-derived T/ET could be
632 attributed to the impact of the drying of stems (and water stress) on the SF-derived T.
633 Regarding VPD, the largest R (+0.6) is still obtained with Lys-derived T/ET. As VPD
634 characterizes the drying ability of air, plants tend to transpire more when VPD (moderately)
635 increases. The positive sign of the correlation between T/ET and VPD illustrates this effect,
636 by considering that E (underneath the wheat canopy) is less affected by VPD than T.
637 However, the correlation values are significantly lower than for NSSM. Regarding LAI,
638 correlations are very low for Lys-derived T/ET. Such result is expected as the partitioning
639 experiment started when wheat was already well developed.

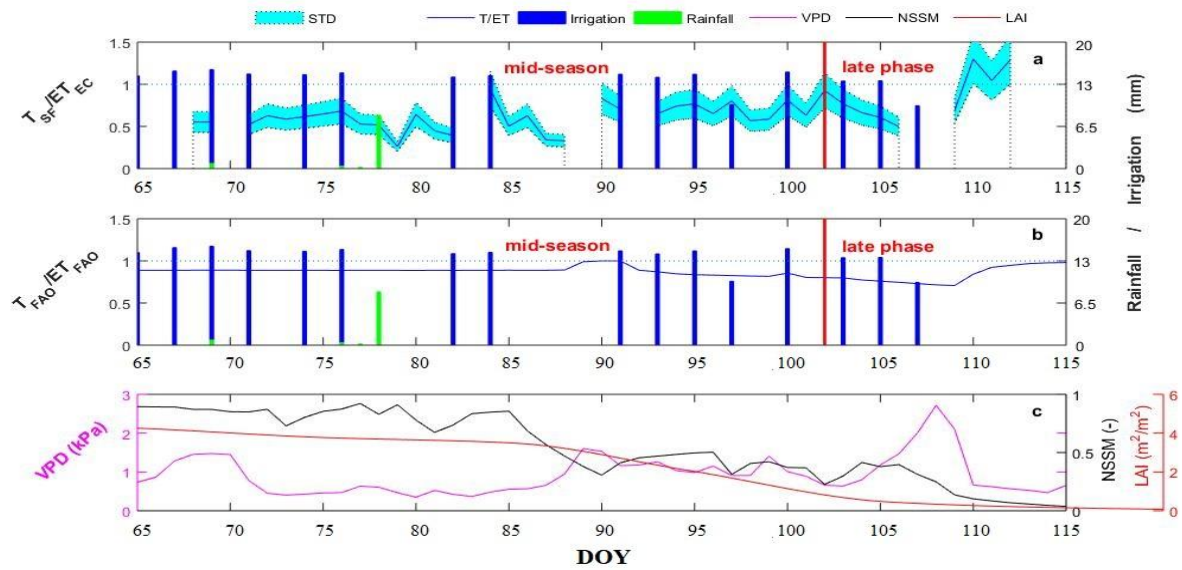


640

641 Figure 11: Evolution of the T/ET ratio, with its standard deviation, derived from Lys (a),
 642 Lys/EC (b), SF/EC (c), SF/Lys (d) and FAO (e) data over the controlled stress field. The
 643 dynamics of NSSM, LAI and VPD are also plotted for comparison (f).

644 *3.3.2 Reference field*

645 Figure 12a plots the T/ET ratio derived from SF/EC data over the reference field. Note that
 646 the gaps in T/ET data are mainly related to gaps in EC data. The large fluctuations observed
 647 over the controlled stress field at the beginning of the period do not appear over the reference
 648 field, as the reference field did not experience water stress and the stem diameter was
 649 sufficient to ensure a good contact with SF sensors as soon as DOY 65. However, the T/ET
 650 ratio also reached values larger than 1 at the end of the senescence stage, consistent with the
 651 results obtained over the controlled stress field. By removing the erroneous behavior of SF-
 652 derived T after DOY 109, the partitioning ratio slightly increases during the study period,
 653 consistent with the Lys-derived T/ET ratio over the other (controlled stress) field. Over the
 654 reference field, the portion of SF/ET/Lys-derived E is relatively large as the soil was
 655 maintained near field capacity with frequent and regular irrigations.



656

657 Figure 12: Evolution of the T/ET ratio, with its standard deviation, derived from SF/EC (a)
 658 and FAO (b) data over the reference field. NSSM, LAI and VPD are also plotted for
 659 comparison (c).

660 Table 3: Statistical results in terms of correlation coefficient (R) between T/ET ratios and
 661 variability factors (SSM, VPD and LAI) over the controlled stress and reference field
 662 separately for the entire study period (by excluding the senescence period in parenthesis).

Field	T/ET	R		
		SSM	VPD	LAI
Controlled stress	T_{SF}/ET_{EC}	-0.46 (-0.18)	0.12 (0.53)	-0.38 (-0.07)
	T_{SF}/ET_{Lys}	-0.64 (-0.48)	-0.30 (-0.18)	-0.08 (0.34)
	$(ET_{Lys}-E_{Lys})/ET_{Lys}$	0.82 (0.72)	0.34 (0.58)	0.17 (-0.57)
	$(ET_{Lys}-E_{Lys})/ET_{EC}$	0.69 (0.62)	0.57 (0.46)	-0.16 (-0.72)
Reference	T_{SF}/ET_{EC}	-0.61 (-0.40)	-0.02 (0.12)	-0.58 (-0.35)

663

664 4. Conclusion:

665 The partitioning of the wheat field ET into T and E is subject to significant uncertainties due
 666 to both the large range (0 to 0.9) covered by the daily T/ET ratio and the difficulty in
 667 separating the T (or E) component from the total ET. Although past studies have been based
 668 on only two independent methods to represent three fluxes (E, T, and ET), an original
 669 experiment is proposed herein 1) to implement four independent methods including three
 670 measurement techniques (EC, Lys and SF) and one modeling approach (FAO-2Kc) over two
 671 drip-irrigated wheat fields with different irrigation regimes, 2) to assess the systematic and
 672 random uncertainties in each partitioning method and 3) to analyze the dynamics of the daily
 673 T/ET ratio in relation to several assumed variability factors including SSM, LAI and VPD. To
 674 the knowledge of the authors it is the first time that all four methods (EC, Lys, SF, FAO-2Kc)

675 have been implemented simultaneously over a cropped field. Note that the FAO-2Kc is
676 calibrated using EC and SF data beforehand.

677 One difficulty in evaluating E and T estimates in the case of a mixed cover is that there is no
678 absolute reference partitioning method. Therefore, new approaches are developed to further
679 assess the systematic and random uncertainties in E/T/ET estimates. Regarding systematic
680 errors, each flux (E, T and ET) is estimated in four different ways and the inter-comparison of
681 the four independent estimates provides an insight into possible discrepancies attributed to
682 one given method. It is found that the FAO-2Kc underestimates E and overestimates T while
683 providing accurate estimates of the total ET. Moreover, EC- and Lys-derived ET estimates are
684 quite consistent, except in very wet (dry) conditions when the Lys tends to slightly
685 overestimate (underestimate) ET-derived ET. Despite the small size of mini Lys (30 cm in
686 diameter), the discrepancy between EC- and Lys-derived ET is found to be minor compared to
687 the uncertainties in the other flux estimates. SF-derived and Lys-derived T estimates are on
688 average consistent during the middle-development phase, but significant differences are
689 obtained at the daily scale. During senescence, the SF-derived T gets values larger than EC
690 ET measurements, which indicates that SF sensors are not appropriate when the stems dry.
691 Whereas all measurements techniques agree on the fact that FAO-2Kc underestimates E, only
692 Lys provides E dynamics that are consistent with FAO-2Kc simulations.

693 Regarding random uncertainties, each measurement method is statistically compared against
694 the FAO-2Kc simulated fluxes corrected over a sliding period. In practice, any potential bias
695 in FAO-2Kc is removed at the weekly scale by subtracting the simulated to observed flux.
696 The idea is to consider that the unbiased discrepancy between FAO and observed flux is
697 proportional to the relative random uncertainty of a given measurement technique. It is found
698 that the Lys is the most precise measurement method (more precise than EC and SF methods).
699 The random uncertainty in SF-derived estimates is the largest due to 1) the small number (3-5
700 per crop field) of SF sensors used, which makes upscaling strategies difficult and 2) the
701 impact of water stress (over the controlled stress field) and drying (over both controlled stress
702 and reference fields) of wheat stems on the SF energy dissipation model.

703 Time series of the T/ET ratios derived from four different combinations of the EC, Lys and
704 SF data sets collected from DOY 65 until senescence are finally analyzed. The T/ET ratio
705 generally increases during the mid-season from about 0.50 to about 0.85 at maturity and then
706 drops towards 0 during the senescence period. Interestingly, the T/ET ratio is highly and
707 positively correlated with SSM, whereas no significant correlation is obtained with LAI. Such
708 results are still consistent with past studies (Liu et al., 2002; Kang et al., 2003), which focused
709 on the wheat development phases with increasing LAI, while our experiments started when
710 the green LAI was already decreasing and lasted until the end of senescence. It is suggested
711 that, in such an arid environment and during the phenological stages when the soil is well
712 covered, SSM is a meaningful proxy for the soil water availability to wheat T. Even though
713 the estimated relative random uncertainties in all the T/ET ratios are acceptable (they all range
714 within 19%-24%), systematic errors in SF measurements lead to values larger than 1 during
715 water-stress and senescence periods. Increasing the number of SF sensors could help reduce

716 the random uncertainties of T estimates under well-watered conditions, especially by
717 improving the upscaling of stem-based measurements to the field scale.

718 Results in this study show that the comparison between detailed (and high quality)
719 measurements against model simulations of E, T and ET is essential to improve models. It is
720 clear that such expensive instruments (eddy covariance, lysimeters, sap flow sensors) cannot
721 be implemented extensively and that the assessment of water use patterns in irrigated crops
722 will still rely on models such as the FAO-2Kc or other models. However, models are not
723 exempt from uncertainties -including systematic biases- in simulated fluxes and soil moisture,
724 especially when they are applied to specific conditions (i.e. drip irrigation) for which they
725 have not been calibrated. In our case, drip irrigated wheat in semi-arid climate, the FAO-2Kc
726 underestimates E compared to field measurements. This underestimation of E may be due to
727 the representation of soil layers as simple reservoirs, which do not take into account the
728 diffusion of water especially between the surface and the root-zone soil layers. To improve the
729 modeling of the surface soil moisture dynamics, it is necessary to consider the capillary rise
730 from the root zone. One question that still remains open is how to represent a complex
731 phenomenon (e.g. water diffusion) using a limited input data set (meteorological
732 measurements) and a simple (two-layer) discretization of the soil as in the FAO-2Kc
733 formalism. Another avenue for research is to adapt the Kr representation to the nonlinear
734 relationship between E and soil moisture in a range of soil types and surface conditions
735 (Merlin et al., 2016; 2018).

736 This experiment provides a unique data set that will be used in the near future to improve land
737 surface models like FAO-2Kc, dual source energy balance models (e.g. Aït Hssaine et al.,
738 2018) and Soil Vegetation Atmosphere Transfer models (e.g. Boone et al., 2017), as the E/T
739 partitioning exerts a strong physical constraint on the surface-atmosphere transfers. Moreover,
740 new partition methods using EC data (e.g. Anderson et al., 2017) could be directly evaluated
741 using the available independent E/T measurements. Estimates of T alone could also be used to
742 investigate vegetation stress indices based on thermal infrared data, fluorescence and
743 Photochemical Reflectance Index (Moreno et al., 2017; Drusch et al., 2017). Such research
744 activities will improve our knowledge about the actual water needs of irrigated crops.

745

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757

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930

931

932 **Appendix A:**

933 The SFL system is fully automated and provides continuous measurements of precipitation
 934 (P) or irrigation during rainfall/irrigation events and ET at any other time. In addition, it
 935 measures the water drainage (D) at the Lys bottom, which makes it possible to determine the
 936 refilling capacity of groundwater at a certain depth of soil. The determination of the water
 937 balance components is based on the variations of the weight of: 1) the soil column in the Lys
 938 and 2) a drainage bottle connected to the Lys bottom. The SFL scales provide weight data at
 939 the 1 min time step. Another special feature of the SFL system is that each Lys is tension-
 940 controlled, meaning that the soil water tension inside the Lys is regulated by pumping in or
 941 pumping out water at the Lys bottom so as to closely follow the soil water tension measured
 942 in real field conditions (outside the Lys) at the same depth. Therefore, the system
 943 continuously ensures that the Lys bottom boundary conditions are representative of field
 944 conditions at the same depth.

945 ET and rainfall/irrigation are estimated as the residual term of the water balance. Note that the
 946 lysimetric measurement principle cannot estimate both input and output terms simultaneously
 947 during the elementary measurement period (defined as the period between two weight
 948 measurements). The P calculation is based on the assumption that during the elementary
 949 period (set to 10 min in our case), P is much larger than ET so that ET is negligible.
 950 Therefore, ET is set to zero during rainfall/irrigation events:

$$951 \quad P_{LYS} = \Delta S_{LYS} + D_{LYS} \quad (A1)$$

952 with P_{LYS} (mm/10 min) being the confounded volumes of rainfall and irrigation and ΔS_{LYS}
 953 (mm/10 min) the variation of the water volume stored in the Lys calculated over a period of
 954 10 min. The storage term is estimated as:

$$955 \quad \Delta S_{LYS} = [(L_m(t) - L_m(t - 10))] * 14.15 \quad (A2)$$

956 where $L_m(t)$ (kg) is the weight of the soil column in the Lys at time t [min], and the coefficient
 957 14.15 corresponds to the conversion factor used to convert weight differences into mm of
 958 water per m^2 of surface area. In fact, the disk surface of the SFL Lys is $0.0707 m^2$, so that a 1
 959 kg change in mass corresponds to 14.15 mm of water per m^2 . Similarly, the D term is
 960 estimated as:

$$961 \quad D_{LYS} = [S_m(t) - S_m(t - 10)] * 14.15 \quad (A3)$$

962 where $S_m(t)$ (kg) is the weight of the D bottle at time t (min). To reduce random uncertainties
 963 in S_m and L_m measurements, the average of 3 successive (1-min) measurements around time t
 964 is taken for the computation of D_{LYS} and ΔS_{LYS} , respectively. The daily fluxes (mm/day) are
 965 finally obtained by summing up the 10-min estimates derived in Equations (1-3).

966 For days when there is no irrigation/rainfall, ET is estimated as:

$$967 \quad ET_{LYS} = -\Delta S_{LYS} - D_{LYS} \quad (A4)$$

968 where ET_{LYS} (mm/day) is the daily ET, ΔS_{LYS} (mm/day) the variation of the water volume
 969 stored in the Lys and D_{LYS} (mm/day) the daily drainage. The ΔS_{LYS} and D_{LYS} of Equation (4)
 970 are calculated over a period of 1 day:

$$971 \quad \Delta S_{LYS} = [L_m(t) - L_m(t - 24 * 60)] * 14.15 \quad (A5)$$

$$972 \quad D_{LYS} = [S_m(t) - S_m(t - 24 * 60)] * 14.15 \quad (A6)$$

973 To reduce random uncertainties in L_m and S_m and measurements in Equations (A5) and (A6),
 974 respectively, the average of 15 successive (1-min) measurements around time t (midnight) is
 975 taken for the computation daily fluxes.

976 For days when an irrigation episode occurs, the weight generated by irrigation water is
 977 subtracted to the daily ET estimated in Equation (4). In practice, the variation of the Lys
 978 weight is expressed as:

$$979 \quad \Delta S_{LYS} = \Delta S_{LYS,1} + \Delta S_{LYS,2} \quad (A7)$$

980 with $\Delta S_{LYS,1}$ and $\Delta S_{LYS,2}$ being the storage variations associated with the ET outside the
 981 irrigation period and the ET during the irrigation period, respectively. The first term of
 982 Equation (7) is computed as:

$$983 \quad \Delta S_{LYS,1} = \{ [L_m(t) - L_m(t - 24 * 60)] - [L_m(t_{EI}) - L_m(t_{SI})] \} * 14.15 \quad (A8)$$

984 where t_{SI} and t_{EI} are the start and end time of irrigation, respectively. The second term is
 985 computed as:

$$986 \quad \Delta S_{LYS,2} = (t_{EI} - t_{SI}) * Q_d - [L_m(t_{EI}) - L_m(t_{SI})] * 14.15 \quad (A9)$$

987 where Q_d is the hourly flow rate of the dripper at the Lys level.

988 For days when a rainfall episode occurs, daily ET is estimated in the same way as for
 989 irrigation days, except that the $\Delta S_{LYS,2}$ term in Equation (7) is set to zero. It is thus assumed
 990 that the ET during rainfall events is negligible compared to the daily ET due to a lower
 991 potential evaporative demand in the presence of clouds.

992

993 **Appendix B:**

994 SHB sensors are composed of a heating resistor, a thermopile and two thermocouples on
 995 either side of the resistor. The heating resistor is applied around the stem with the
 996 thermocouples. Insulation is added all around the devices to avoid any external thermal bias.
 997 It can therefore be considered that the only heat energy received by the section of the stem
 998 comes from the heating resistor, denoted P_{in} and expressed in W unit (Smith & Allen, 1996).

999 The energy P_{in} received by the stem is divided into four diffusion factors:

$$1000 \quad P_{in} = q_v + q_r + q_f + q_s \quad (B1)$$

1001 with q_v corresponding to the energy diffused vertically in the stem by conduction, q_r the radial
1002 energy lost by conduction, q_f the energy diffused via the SF by convection, and q_s the change
1003 rate of the heat storage.

1004 Considering that the conditions of the system are stationary, q_s is often ignored. Senock and
1005 Ham (1993) investigated the effect of this parameter on the flux calculation for a soybean
1006 stem and found that q_s accounts for only 3% of the total daily thermal flux. In this case, q_s had
1007 no significant effect on the estimated SF.

1008 Once all the fluxes (P_{in} , q_v and q_r) are determined, the intensity of the sap flux F (g/hour) can
1009 be calculated as:

$$1010 \quad F = \frac{P_{in} - q_v - q_r}{C_e * dT} \quad (B2)$$

1011 where C_e ($J \cdot g^{-1} \cdot ^\circ C^{-1}$) is the specific heat of water and dT ($^\circ C$) the sap temperature difference
1012 between the base and the top of the heating element. As the flux calculated in Equation (B2) is
1013 representative of a single stem, an upscaling strategy is needed to extrapolate this result at the
1014 1 m^2 scale:

$$1015 \quad T_{SF} = \frac{(F * N_{st})}{1000} \quad (B3)$$

1016 where T_{SF} (mm/hour) is the SF-derived T and N_{st} the number of stems per m^2 .

1017

1018 **Appendix C:**

1019 The main equations of the FAO-2Kc approach are briefly reminded below. For more details,
1020 please refer to the FAO-56 documentation (Allen et al., 1998) and related published work
1021 (e.g. Er-Raki et al., 2007, Le Page et al., 2014).

1022 In the FAO-2Kc approach, the evolution of K_{cb} is subdivided into four growth phases. At
1023 beginning of the culture, the plant emerges and is created during the initial phase (I_{ini}). Then
1024 the plant experiences a rapid increase during the so-called development phase (I_{dev}). Later, the
1025 development reaches its maximum during the mid-season phase (I_{mid}). Finally, the senescence
1026 occurs during the end-of-season phase (I_{late}), which lasts until harvest. The K_{cb} parameter is
1027 thus decomposed into $K_{cb,ini}$, $K_{cb,dev}$, $K_{cb,mid}$ and $K_{cb,end}$ for the initial, development, mid-season
1028 and end-of-season periods, respectively. The K_{cb} was interpolated during the growth phase as
1029 in the FAO-56 documentation. In practice, the $K_{cb, \text{mid-season}}$ was linearly interpolated using the
1030 initial K_{cb} . Lengths of growth stages (I_{ini} , I_{dev} , I_{mid} , I_{late}) are usually calculated based on the
1031 fractional vegetation cover f_c .

1032 The E coefficient K_e is calculated as:

$$1033 \quad K_e = \min (K_r * (K_{c,max} - K_{cb}), f_{ew} * K_{c,max}) \quad (C3)$$

1034 where $K_{c,max}$ is the maximum value of K_c following rain or irrigation, K_r is the dimensionless
 1035 E reduction coefficient dependent on the cumulative depth of water depleted (evaporated)
 1036 from the topsoil and f_{ew} is the fraction of the soil that is both exposed and wetted. The K_e
 1037 coefficient changes rapidly to a maximum value after a precipitation or irrigation event, and
 1038 then decreases to zero when the soil surface dries out with very little or no E. The calculation
 1039 of this coefficient requires a daily water balance for the soil surface layer with an effective
 1040 depth Z_e . The calculation procedure requires input soil parameters such as the soil moisture at
 1041 field capacity (Θ_{fc}) and at the wilting point (Θ_{wp}), the readily evaporable water (REW), and
 1042 the depth of Z_e .

1043 The determination of K_s requires a daily calculation of the water balance for the root zone
 1044 (with depth Z_r). The water supply in the root zone is reflected through the root zone depletion
 1045 (D_r). At Θ_{fc} , D_r is zero and $K_s = 1$ (no stress). Water stress occurs when the D_r becomes
 1046 greater than the depth of readily available water (RAW) in the root zone. For $D_r > RAW$, K_s is
 1047 given by Allen et al. (1998):

$$1048 \quad K_s = \frac{TAW - D_r}{(1-p)*TAW} \quad (C4)$$

1049 where p is the fraction of TAW (total available water) that a crop can extract from the root
 1050 zone under no water stress conditions. TAW is derived from Z_r , Θ_{fc} and Θ_{wp} . The
 1051 recommended p value for winter wheat is 0.55 when ET_c is 5 mm/day (FAO-56, Table 22).
 1052 When ET_c differs from 5 mm/day, p can be adjusted using the following approximation:

$$1053 \quad p = 0.55 + 0.04 * (5 - ET_c) \quad (C5)$$