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1 **Evaluation of a simple approach for crop**
2 **evapotranspiration partitioning and**
3 **analysis of the water budget distribution for**
4 **several crop species**

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16 Abstract

17

18 Climate variability and climate change induce important intra- and inter-annual variability of
19 precipitation that significantly alters the hydrologic cycle. The surface water budgets and the plant or
20 ecosystem water use efficiency (WUE) are in turn modified. Obtaining greater insight into how
21 climatic variability and agricultural practices affect water budgets and regarding their components in
22 croplands is, thus, important for adapting crop management and limiting water losses. Therefore, the
23 principal objectives of this study are:

- 24 1) to assess the contribution of different components to the agro-ecosystem water budget and
25 2) to evaluate how agricultural practices and climate modify the components of the surface
26 water budget.

27 To achieve these goals, we tested a new method for partitioning evapotranspiration (ETR),
28 measured by means of an eddy-covariance method, into soil evaporation (E) and plant transpiration
29 (TR) based on marginal distribution sampling (MDS). The partitioning method proposed requires
30 continuous flux recording and measurements of soil temperature and humidity close to the surface,
31 global radiation above the canopy and assessment of leaf area index dynamics. This method is well
32 suited for crops because it requires a dataset including long bare-soil periods alternating with
33 vegetated periods for accurate partitioning estimation.

34 We compared these estimations with calibrated simulations of the ICARE-SVAT double source
35 mechanistic model. The results showed good agreement between the two partitioning methods,
36 demonstrating that MDS is a convenient, simple and robust tool for estimating E with reasonable
37 associated uncertainties. During the growing season, the proportion of E in ETR was approximately
38 one-third and varied mainly with crop leaf area. When calculated on an annual time scale, the
39 proportion of E in ETR reached more than 50%, depending on the crop leaf area and on the duration
40 and distribution of bare soil within the year.

41 Keywords

42 Crop; Evapotranspiration; Transpiration; Evaporation; Water budget; Partitioning; land-
43 surface model

1. Introduction

45 Agricultural water resource limitations have become a major issue as the Earth's population
46 has drastically increased, leading to a corresponding increase in food demand. Furthermore, global
47 climate change will locally impact the mean and variance of temperature as well as the amount and
48 distribution of precipitation and atmospheric CO₂ concentrations (IPCC, 2007). Agriculture will be
49 strongly impacted by these changes (Brouder and Volenec, 2008). In this context, quantifying and
50 understanding the drivers of the water cycle components, such as climate variability, climate change
51 and crop rotations, are essential for facing both agro-economic and environmental challenges.

52 Allen (2008) documented methods related to the calculation of evapotranspiration (ETR),
53 from experimental and modeling methods using different time and space scales. For all of these
54 methods, which spatial scales ranged from local soil water sampling, lysimeters and eddy covariance
55 (EC) to scintillometry, the reality that an improperly designed experiment or measurement can lead to
56 highly erroneous water use estimates is evident. For ETR partitioning between evaporation (E) and
57 transpiration (TR), sapflow measurements (Granier et al., 1996; Roupsard et al., 2006; Steppe et al.,
58 2010) and isotope techniques (Williams et al., 2004) combined with EC measurements over forests
59 have been used to estimate E and TR at the canopy scale. In other studies, two levels of EC
60 measurements have been used to infer the TR and WUE of the forest canopy itself (Jarosz et al., 2008;
61 Lamaud et al., 1996; Roupsard et al., 2006), as fluxes from the soil and understory can constitute a
62 significant portion of the total ecosystem flux. Over croplands, gas exchange measurements at the leaf
63 scale (Medrano et al., 2009; Steduto and Albrizio, 2005; Steduto et al., 1997) and lysimeter
64 measurements (Qiu et al., 2008; Steiner and Hatfield, 2008) have also been used to analyse the
65 different components of ETR at the plant or canopy scale.

66 Empirical modeling approaches based on energy balance formulations have been used to
67 estimate TR (Li et al., 2008; Ritchie, 1972), but large differences compared to TR estimation using
68 sapflow measurements have been observed (Sauer et al., 2007). When using mechanistic modeling to
69 infer TR, one-source (vegetation plus soil as a whole) (Chen et al., 1996; Koren et al., 1999; Noilhan
70 and Mahfouf, 1996; Noilhan and Planton, 1989), two-source (soil plus vegetation, separately) (Gentine
71 et al., 2007; Hu et al., 2009; Sellers et al., 1996; Shuttleworth and Wallace, 1985), three-source (bare
72 soil, shaded soil and vegetation) (Boulet et al., 1999), or multiple-source (Ogée et al., 2003) soil
73 vegetation atmosphere transfer (SVAT) models can be used. The use of two (or more) sources in
74 models allows for a more realistic representation of the energy budget and can describe the respective
75 contributions of the soil and vegetation to ETR. However, although more complex SVATs may be
76 more mechanistic, they require more input parameters, which involve complicated calibrations and
77 often the solution might be ill-defined (Beven, 2006). If the complex model is calibrated over a short

78 period and with too few observed variables, a correct ETR can be obtained with incorrect E-TR
79 partitioning. The right answer is obtained yet for the wrong reason. All of these TR estimation
80 methods raise questions regarding their spatial representativeness, the generalization of their
81 applicability, and the complexity of the modeling tools used.

82 In the present study, the main objectives are 1) to assess the different components of the
83 annual crop water budget and 2) to evaluate a simple and generic method for partitioning ETR into
84 soil and vegetation components. The advantage of such simple method is that it can be easily used in
85 other regions with minimum calibration effort. The obtained result is thus more robust than more
86 complex models, which would require recalibration.

87 EC measurements of water fluxes were performed continuously over a period of 2 years above
88 winter and summer crops in the southwest of France to highlight the contribution of each component
89 to the agro-ecosystem water budget and the impact of different crop species in relation to climatic
90 conditions on each of them. From these measurements, we developed a new methodology based on
91 marginal distribution sampling (MDS) to infer the partitioning of ETR between E and TR during each
92 crop growing season. We evaluated this methodology against actual data during bare soil periods for E
93 and against a site-calibrated mechanistic modeling approach using the ICARE-SVAT model (Gentine
94 et al., 2007) for both bare soil and vegetated periods.

95 2. Materials and methods

96 2.1. Site and measurement descriptions

97 Since March 2005, micrometeorological, meteorological and vegetation dynamic
98 measurements have been performed at two cultivated plots located 12 km apart near Toulouse in the
99 southwestern part of France located at Auradé (43°54'97''N, 01°10'61''E) and Lamasquère
100 (43°49'65''N, 01°23'79''E). Both sites are part of the CarboEurope-IP Regional Experiment (Dolman
101 et al., 2006) and the CarboEurope-IP Ecosystem Component. They have been cultivated for more than
102 30 years, and they experience similar meteorological conditions but are subjected to different
103 management practices and exhibit different soil properties and topography. The crop rotations on both
104 sites are representative of the main regional crop rotations. Crops from the 2005-06 and 2006-07
105 growing seasons were analyzed in this study. Each crop year was studied on the basis of the
106 hydrologic year, *i.e.*, from the 1st of October, after the summer crop harvest and before the beginning
107 of winter crop sowing at the end of November. The Auradé plot was cultivated with winter wheat
108 (*Triticum aestivum* L.) from 27 October 2005 to 29 June 2006 followed by sunflower (*Helianthus*
109 *annuus* L.) from 11 April 2007 to 20 September 2007. The Lamasquère plot was cultivated with maize
110 (*Zea mays* L.) used for silaging from the 1st of May 2006 to 31 August 2006 followed by winter wheat
111 from 18 October 2006 to 15 July 2007. The Lamasquère site was irrigated in 2006 when maize was
112 cultivated.

113 Turbulent fluxes of water vapor (ETR and latent heat, LE), sensible heat (H) and momentum
114 (τ) were measured continuously by the EC method (Aubinet et al., 2000; Baldocchi, 2003; Grelle and
115 Lindroth, 1996; Moncrieff et al., 1997). EC devices were mounted at heights of 2.8 m at Auradé and
116 3.65 m at Lamasquère. The instrument heights were chosen to be at least 1 m higher than the crops at
117 the time of their maximum development. The EC system consists of a three-dimensional sonic
118 anemometer (CSAT 3, Campbell Scientific Inc., Logan, UT, USA) and an open-path infrared gas
119 analyzer (LI7500, LiCor, Lincoln, NE, USA). EdiRe software (Robert Clement, © 1999, University of
120 Edinburgh, UK) was used to calculate fluxes following CarboEurope-IP recommendations. A 2D
121 rotation was applied to align the stream-wise wind velocity component with the direction of the mean
122 velocity vector. Fluxes were corrected for spectral frequency loss (Moore, 1986). Water fluxes were
123 corrected for air density variations (Webb et al., 1980). Flux filtering, quality controls and gap filling
124 were performed following CarboEurope-IP recommendations.

125 Standard meteorological variables in the air and in the soil were recorded at each site to
126 analyze and correct turbulent fluxes. Destructive vegetation measurements were performed regularly

127 to follow biomass and surface vegetation area dynamics. A complete description of the site
128 characteristics, management practices, biomass inventories, vegetation area measurements,
129 instrumentation setups, flux filtering, quality controls and gap filling procedures is available in Béziat
130 et al. (2009).

131 2.2. Evapotranspiration partitioning between soil evaporation and vegetation 132 transpiration

133 A statistical methodology based on marginal distribution sampling (MDS) (Reichstein et al.,
134 2005) has been designed to partition ETR between E and TR using meteorological variables. The
135 general principle of MDS consists of estimating flux data using the mean of the fluxes under similar
136 meteorological conditions by construction of a look-up table.

137 To access the partition of ETR during the vegetation period, we first construct an MDS dataset
138 linking measured ETR values with meteorological variables during bare soil periods (when ETR is
139 reduced to its E component). Note that, for building the look-up table, we did not use a time moving
140 window as in Reichstein et al. (2005) but the maximum of available data during the bare soil periods
141 before or after the vegetated period. As a result, we estimated E during the period with vegetation
142 using MDS (E_{MDS}) with a similar range of driving variables. Bare soil periods were defined as the
143 period between tillage and sowing. Periods immediately following harvesting, when stubble was still
144 on the ground or when regrowth events occurred, were discarded from the MDS calculation dataset.
145 Table 1 describes the bare soil periods and the corresponding filtered ETR data available for the
146 calculation of E_{MDS} . Vegetation periods were defined for a leaf area index (LAI) threshold above
147 $0.2 \text{ m}^2 \text{ m}^{-2}$ during daytime. Outside of these periods, TR was assumed to be negligible, and E was
148 considered to be equal to the gap-filled ETR measurements.

149 Three variables that can be measured or estimated during both bare soil and vegetation periods
150 were considered as driving factors for E: soil water content at a 5 cm depth (SWC_5), temperature at a
151 5 cm depth (T_{s5}) and net short wave radiation reaching the ground surface (RG_s). We choose not to
152 consider relative humidity and wind speed as driving factors because the first was too difficult to
153 model close to the ground in a fast growing stand and the second is supposed to vanish close to the
154 ground surface during the whole vegetated periods. Additionally, our objective was to test a method
155 that could be easily applied at sites that are equipped with instruments for standard
156 micrometeorological measurements.

157 The bare soil periods occurred during winter and spring before the summer crop season and
158 during summer and autumn before the winter crop season (Table 1). Therefore, even if bare soil
159 periods are shifted in time compared to growing periods, the ranges of SWC_5 , T_{s5} and RG_s
160 encountered during these periods were assumed to be sufficiently large for the calculation of E by

161 MDS during vegetated periods. To set up E_{MDS} , the E-driving variables space was split into regular
 162 intervals; the initial ranges of these intervals were at first fixed at 2 % for SWC_5 , 1 °C for T_{s5} and
 163 25 W m^{-2} for RG_s . As these ranges did not permit the construction of a complete E_{MDS} dataset, they
 164 were increased progressively to threshold values of 8 %, 4 °C and 100 W m^{-2} by steps of 2 %, 1 °C
 165 and 25 W m^{-2} for SWC_5 , T_{s5} and RG_s , respectively. If E_{MDS} was still incomplete (14.5 % and 10.5 % of
 166 the E_{MDS} data were missing after this step at Auradé and Lamasquère, respectively), the standard gap-
 167 filling algorithm defined by Reichstein et al. (2005) and adapted by Béziat et al. (2009) to account for
 168 discontinuity in the field status corresponding to crop functioning periods between dates of sowing,
 169 maximum crop development, harvest and tillage was applied using SWC_5 , T_{s5} and RG_s as driving
 170 variables. Then, during vegetation periods, TR was estimated (TR_{MDS}) as the difference between gap-
 171 filled ETR and E_{MDS} .

172 As RG_s was not measured directly at ground height during vegetation periods, the two-layer
 173 (soil and vegetation) radiative transfer formulation described by Taconet et al. (1986) was used for its
 174 estimation:

175 **Erreur ! Erreur !(4)**

176 where RG is the incident short wave solar radiation at the top of the canopy, a_s is the soil albedo, a_v is
 177 the vegetation albedo, and σ_f is a shielding factor representing the ratio of radiation intercepted by the
 178 vegetation. A mean value of 0.15 for a_s was calculated from incident and reflected RG measurements
 179 during the bare soil periods defined above using a CNR1 (Kipp & Zonen, Delft, NL). Temporal
 180 dynamics of a_v were calculated based on the proportions of green leaf area index (LAI_g) and senescent
 181 (yellow) LAI (LAI_y) compared to total LAI ($LAI_{tot} = LAI_g + LAI_y$):

182 **Erreur !Erreur !(5)**

183 where a_g and a_y indicate the albedo of green and senescent vegetation, respectively. For all crops, a
 184 mean value of 0.2 for a_g and 0.25 for a_y was estimated following Hartmann (1994). Continuous LAI_g
 185 values were obtained by spline interpolation of destructive LAI measurements performed monthly
 186 during the slow growing period and every two weeks during the fast growing period (Béziat et al.,
 187 2009). LAI_y dynamic was estimated based on the maximum LAI_g (LAI_{max}) as follows:

$$188 \quad LAI_y = r \cdot LAI_{max} - LAI_g \quad (6)$$

189 where r is the LAI reduction coefficient accounting for surface losses caused by the falling and drying
 190 of leaves during senescence. We considered r as varying linearly from 1 at LAI_{max} to 0.8 at harvesting.
 191 Calculation of σ_f was carried out by means of a Beer-Lambert-type law:

192
$$\sigma_f = 1 - e^{(-k \cdot LAI_{tot})} \quad (7)$$

193 where k is the extinction coefficient according to the incident direction ($\Omega_s = (\theta_s, \phi_s)$, described by the
 194 zenithal and azimuthal solar angles, respectively). The k formulation proposed by Goudriaan (1977)
 195 was used:

196 **Erreur !Erreur !**(8)

197 where $G(\Omega_s)$ indicates the ratio of effective LAI_{tot} , according to Ω_s . In our case, leaf orientation was
 198 assumed to be azimuthally symmetrical and spherical, and therefore, $G(\Omega_s) = G(\theta_s) = 0.5$. The $\sqrt{1-a_v}$
 199 term was introduced by Goudriaan (1977) to account for the influence of diffusion on transmittance.

200 2.3. SVAT model description and calibration

201 The model proposed in this study as a second approach to evaluate the partitioning of ETR
 202 into TR and E is the Soil Vegetation Atmosphere Transfer (SVAT) model known as ICARE (Gentine
 203 et al., 2007). This model was developed to provide as physical as possible a representation of the main
 204 processes involved in the soil-plant-atmosphere system. Two layers are considered at the surface: one
 205 for vegetation and one for the underlying bare soil. The energy budget is solved for each component
 206 according to Shuttleworth and Wallace (1985) and as described in Braud et al. (1995). The soil is
 207 divided into two reservoirs, a surface reservoir and a deep reservoir with a water balance formalism
 208 based on the original ISBA scheme (Noilhan and Mahfouf, 1996; Noilhan and Planton, 1989). The soil
 209 water content and temperature dynamics are solved following the *force-restore* method applied by
 210 Deardorff (1977). ETR and H flux are controlled by a succession of resistances that provide a simple,
 211 yet physically realistic description of the transition of energy and mass between bare soil and the
 212 closed canopy. There are five resistances involved in this model (Figure 1): the canopy stomatal
 213 resistance (r_{sto} , $s\ m^{-1}$), the soil surface resistance (r_{ss} , $s\ m^{-1}$), the aerodynamic resistance between the
 214 ground surface and the top of the canopy (r_{as} , $s\ m^{-1}$), the canopy boundary layer resistance (r_{ac} , $s\ m^{-1}$)
 215 and the aerodynamic resistance between the top of the canopy and a reference level above the canopy
 216 (r_a , $s\ m^{-1}$). All aerodynamic resistances are based on Choudhury and Monteith (1988) and include the
 217 atmospheric static-stability correction based on Monin-Obukhov Similarity Theory (MOST).

218 Three resistances are critical for this study because of their contribution to partitioning ETR
 219 between E and TR. The first resistance is r_{ss} , which controls soil E. It was formulated as an
 220 exponential function of the relative surface soil water content (Passerat De Silans et al., 1989):

221 **Erreur !Erreur !**(9)

222 where SWC_s and SWC_{sat} represent the near-surface soil water content and soil porosity ($m^3 m^{-3}$),
223 respectively, and A_{fss} is an empirical factor. r_{ss} exponentially increase with soil drying. The second
224 resistance is r_{sto} , which is extremely important for the canopy state variable dynamics law that
225 primarily controls TR. The r_{sto} parameter was expressed following the classic Jarvis (1976)
226 representation as presented in Noilhan and Planton (1989):

227 **Erreur !Erreur !(10)**

228 where r_{smin} is the minimum stomatal resistance function, and f_i are stress factors with values between 1
229 and 0, depending on global solar radiation (RG), water stress estimated from the current SWC in the
230 rooting zone (SWC_r) and the SWC at the wilting point (SWC_{wilt}), the air vapor pressure deficit (VPD)
231 and the temperature of the air and canopy (T_a and T_c , respectively). The use of bare soil and vegetated
232 conditions allows nearly independent calibrations of the soil and canopy water resistances.

233 The third resistance is r_a , which controls both TR and E for water balance. It is calculated as in
234 Brutsaert (1982):

235 **Erreur !Erreur !(11)**

236 where z_r and d are the reference and displacement heights, respectively; z_{oh} is the thermal roughness
237 length; ψ_h represents the integral adiabatic correction function for heat; L_{mo} is the Monin-Obukhov
238 length; K is the Von Karman constant; and u^* is the friction velocity. In our application, z_{oh} is linked
239 with z_o , the momentum ratio, by a constant ratio. For more details on resistance calculations and
240 formalisms, see the appendix of Gentine et al. (2007).

241 To run the model and obtain reliable estimates of ETR partitioning, some variables measured
242 *in situ* were forced as model inputs. These variables included 1) atmospheric variables (incoming
243 shortwave radiation, precipitation, temperature and relative humidity of air and wind speed) measured
244 routinely at each site at a half-hourly time intervals; 2) vegetation dynamic variables (LAI_g , LAI_y and
245 vegetation height) at daily time intervals interpolated from *in situ* measurements (see section 2.2); and
246 3) the total (soil plus vegetation) mean daily albedo calculated as the ratio between outgoing and
247 incoming shortwave radiation and measured at each site with a CNR1 (Kipp & Zonen, Delft, NL).
248 Shortwave radiative transfer through the canopy was estimated following the same equations as
249 employed for the calculation of RG_s in the MDS approach (Equations (4) to (8)). For longwave
250 radiative transfer, the original ISBA formulation was used. Finally, the model calculates the dynamics
251 of 1) the land-surface energy balance terms: net radiation (R_n), H , LE and its two components (E and
252 TR) and soil heat flux (G); 2) the SWC of the two soil layers (the surface and rooting zones, with
253 potential extraction fixed at 1.5 m for both sites); and 3) the surface and deep soil temperatures as well
254 as canopy and radiative temperatures.

255 In this study, the model was adjusted to fit the main half-hourly components of the energy
256 (Rn, LE and H) and water budgets (SWC) measured at both sites. We chose not to assimilate the
257 measured SWC_5cm in the model to control soil surface conditions but to calibrate surface resistance
258 to bare soil evaporation. As a result soil water budget is closed at both half-hourly and daily time step.
259 Optimization of model outputs was performed independently for each site (Auradé and Lamasquère).
260 Calibration of the model parameters was performed in two steps. The first step of optimization was
261 based only on the bare soil periods defined in section 2.2 (Table 1) to fit r_{ss} and r_a . This soil calibration
262 thus accounts for the site-specific soil response to E. Two parameters were considered as the most
263 sensitive and significant: A_{rss} and the ratio z_0/z_{0h} , which are involved in the r_{ss} and r_a formulations
264 (Equations (9) and (11)), respectively. The second step of optimization was performed for the
265 vegetation periods to optimize the vegetation control on TR: r_{smin} and SWC_{wilt} (Equation (10)).
266 Optimization was performed by maximizing the sum of the Nash criteria (Nash and Sutcliffe, 1970)
267 for SWC, LE, H and Rn. The Nash criterion is given by:

268 **Erreur !Erreur !(12)**

269 where X represents the simulated data and Y the observed data. The Nash criterion has the advantage
270 of being dimensionless, meaning that the addition of criteria gave the same importance to variables
271 considered in the optimization process. The criterion is less sensitive than the root mean square error
272 (RMSE) to extreme values. The values of the optimized parameters are summarized in Table 2. ETR,
273 E and TR were finally modeled for each site using the mean of the best-fit parameters A_{rss} and the
274 z_0/z_{0h} ratio for each bare soil period added to the best-fit parameters r_{smin} and SWC_{wilt} specific to each
275 crop growing season.

276 2.4. Application and evaluation of the partitioning methods

277 Over bare soil periods (Table 1), it was possible to evaluate and compare soil E estimated by
278 both the MDS approach and the ICARE-SVAT model simulations (E_{MDS} and E_{ICARE} , respectively). For
279 this analysis, half-hourly data over bare soil were randomly split into two datasets: a calibration
280 dataset and a validation dataset. For ICARE-SVAT, A_{rss} from r_{ss} and z_0/z_{0h} from r_a were fitted for each
281 bare soil dataset at each site (Table 2) on the calibration dataset. Next, a simulation using the mean of
282 the best fit parameters at each site was conducted to compare E estimations with the validation dataset.
283 The same methodology was applied to the MDS method with the same randomly selected datasets.
284 Note that, the dataset previously named calibration is there used for the construction of MDS. This
285 exercise was carried out to compare the performance of the MDS method with that of ICARE-SVAT
286 during bare soil periods. The results presented in Table 5 are discussed in section 3.3. We used the
287 slope and the intercept of the linear regression, the determination coefficient (R^2), the root mean

288 square error (RMSE), the mean bias and the Nash criterion as statistical criteria to evaluate the
289 partitioning methods and compare them with measurements. Thereafter, the complete bare soil dataset
290 was used to calibrate MDS and ICARE-SVAT.

291 At the end of 2005 at Lamasquère, significant regrowth of weeds and previously harvested
292 crops (Triticale) was observed on the plot between 1 October 2005 and 1 December 2005, with the
293 latter date corresponding to the date of ploughing. Consequently, a LAI_g of $0.7 \text{ m}^2 \text{ m}^{-2}$, estimated from
294 hemispherical photographs (Demarez et al., 2008) taken on 22 September 2005, was forced in both
295 methods to estimate the partitioning between E and TR during this period. As the photographs were
296 taken at the beginning of the regrowth event, the constant LAI value used over this two-month period
297 was probably underestimated compared to the true LAI, even if growth was limited during this part of
298 the year. However, this forcing was required for ICARE-SVAT to estimate a more reliable annual
299 ETR.

300 In the ICARE-SVAT model, the evaporation of water intercepted by vegetation is taken into
301 account by the filling of a foliar reservoir which maximum capacity by unit of soil depends on the type
302 of crop, the LAI value and the leaf effective fraction for interception (Dickinson 1984). Following
303 Deardorff (1978), the fraction of foliage moistened by intercepted rain evaporates at potential rate. In our
304 study, this evaporation was accounted for in TR. In the ETR measurements, this term was generally
305 not captured because the data were filtered during rain (or irrigation) events and during the following
306 half hour (Béziat et al., 2009). Therefore, gap-filled ETR data are slightly underestimated as the
307 gapfilling methods are constructed on rain free events. As the maximum annual simulated value for
308 the evaporation of intercepted water was 17 mm at Lamasquère in 2006-07 (3.4 % of the annual
309 simulated ETR), we assumed that this term did not significantly affect the cumulative water flux
310 comparison for the two partitioning methods.

311 2.5. Water budget evaluation

312 The water budget was analyzed seasonally and annually using the following equation:

$$313 \quad P (+I) - \Delta SWC = ETR + (D + R) \quad (13)$$

314 where P is the precipitation measurement; I is irrigation provided by the farmer; ΔSWC is the
315 integrated soil water content difference between the end and the beginning of the period; and D and R
316 are the drainage and runoff terms, respectively. The $P (+I) - \Delta SWC$ term represents the available
317 water for the ecosystem during the period considered. For this analysis, ΔSWC was integrated from
318 the surface to a depth of 100 cm (ΔSWC_{0-100}) using the SWC profile measurements. The $ETR + (D +$
319 $R)$ term represents water lost from the ecosystem. The $(D + R)$ term was calculated as the difference

320 between $P (+I) - \Delta SWC$ and the observed ETR. Therefore, $(D + R)$ reflects both surface and deep
321 water losses and uncertainties in the $P (+I)$, ΔSWC and ETR measurements.
322

323 3. Results and discussion

324 3.1. Seasonal ETR and SWC dynamics

325 During the growing season, the ETR dynamics closely followed the LAI dynamics (Figure 2).
326 For winter wheat crops, the maximal ETR (ETR_{max}) was observed in the middle of May, *i.e.*, at the
327 beginning of senescence, whereas for the summer crops maize and sunflower, ETR_{max} was reached in
328 the middle of July, corresponding to the LAI maximum (LAI_{max}). The delay in ETR_{max} compared to
329 LAI_{max} observed for winter wheat crops may be explained by the seasonal dynamics of R_n , which
330 reaches its maximum at the end of June. Therefore, ETR continuously increased after LAI_{max} was
331 achieved. The vegetation then dried, and the R_n was preferentially dissipated through H , which
332 increased following R_n .

333 The mean maximum ETR was 4.8 mm d^{-1} for winter wheat (ranging between 4.2 and
334 5.4 mm d^{-1}). The difference in the ETR_{max} observed between both winter wheat crops, favoring of the
335 Lamasquère site, may be explained by the original LAI differences in the varieties or better
336 development due to milder and wetter climatic conditions (Figure 2) (Tallec et al., submitted). For
337 winter wheat, Steduto and Albrizio (2005) reported a similar ETR_{max} value (4.4 mm d^{-1}) to the one
338 observed at our study sites and with a similar LAI_{max} . For summer crops, the mean maximum ETR
339 values were 5.1 and 5.6 mm d^{-1} for sunflower and maize, respectively. Nevertheless, Suyker and
340 Verma (2008) reported higher ETR_{max} values for summer crops, ranging between 6.5 and 8 mm d^{-1} for
341 irrigated soybeans and maize, respectively. This difference in the ETR response can be explained by a
342 lower LAI_{max} value of $3.3 \text{ m}^2 \text{ m}^{-2}$ for maize compared to the LAI values higher than $5.5 \text{ m}^2 \text{ m}^{-2}$
343 observed by Suyker and Verma (2008). The reduced maize development observed in our field was a
344 consequence of less irrigation being used and differences in crop varieties and management practices,
345 as explained in Béziat et al. (2009). Similarly for sunflower crops, Steduto and Albrizio (2005) and
346 Karam et al. (2007) reported an ETR_{max} twice as high as that measured at Auradé over sunflower plots
347 that were either irrigated or not, probably resulting from considerably higher LAI_{max} values (between
348 2.8 and $3.5 \text{ m}^2 \text{ m}^{-2}$ in Albrizio and Steduto (2005) and higher than $6 \text{ m}^2 \text{ m}^{-2}$ in Karam et al. (2007)
349 compared to the value observed in the present study. However, when comparing the relative sunflower
350 ETR response to that of other crops, the low LAI_{max} of $1.7 \text{ m}^2 \text{ m}^{-2}$ was not accompanied by a
351 proportionally lower ETR_{max} as for other crops. This was probably caused by high stomatal
352 conductance, which can be more than twice as high as that of maize (Katerji and Bethenod, 1997).

353 At Auradé, the integrated soil water content between 0 and 30 cm deep (SWC_{0-30}) (Figure 2c)
354 decreased during winter wheat development because of low precipitation and root absorption. The

355 same pattern was observed for sunflower, but in this case, SWC_{0-30} began to decrease before the
356 sunflower growing season, which was attributed to low precipitation associated with a Rn increase.
357 We assumed that SWC_{0-30} decreased at Lamasquère during spring 2006 for the same reasons. During
358 maize development, the effect of root absorption on SWC_{0-30} was strong, despite the irrigation
359 employed. During spring 2007, the period of winter wheat development at Lamasquère coupled with
360 the high precipitation level maintained higher SWC_{0-30} values compared to spring 2006. During
361 senescence and after harvesting, low precipitation and high Rn increased ETR (corresponding to E)
362 and caused the soil to dry. The absolute values of SWC_{0-30} were higher at Lamasquère than at Auradé
363 because of two factors: 1) the greater water retention capacity of the soil due to higher clay content
364 and 2) the proximity of the Touch River (about 400 m) inducing water rise in winter by capillarity up
365 to the 0-30cm layer. Therefore, this absolute difference did not necessarily induce a difference in soil
366 water availability for the plants.

367 During non-vegetation periods, ETR (corresponding to E) varied between 0 and 2 mm d⁻¹.
368 This variation was explained in part by variations in Rn. In September 2006, the ETR_{max} was observed
369 to be between 2.5 and 3 mm d⁻¹ at both sites subsequent to important rainfall events (Figure 2c). The
370 same phenomenon was observed at Lamasquère in March 2006 before maize sowing.

371 3.2. Comparison and evaluation of the performance of the partitioning methods

372 Statistical results comparing the ICARE-SVAT model output with the measurements are
373 presented in Table 3. Overall, the different components of the energy budget were well reproduced by
374 the model for both sites and both years. R^2 and Nash criterion values were close to 1, with mean
375 respective R^2 and Nash values of 0.98 and 0.98 for Rn, 0.86 and 0.81 for LE and 0.76 and 0.70 for H
376 being obtained. As expected, the model simulated Rn properly, with a mean slope of 1.00, a mean
377 intercept of 0.97 W m⁻² and an RMSE globally lower than 30 W m⁻². However, a small overestimation
378 of Rn was observed at Auradé, especially in 2006-07 (mean bias equal to 5.67 W m⁻² for both years),
379 and a small underestimation was observed at Lamasquère, especially in 2005-06 (mean bias equal to -
380 3.26 W m⁻² for both years). With respect to Rn, a slight overestimation was observed for LE at Auradé
381 (Figure 3), with a mean slope for this site of 1.09 and a mean bias of 3.68 W m⁻² being observed. In
382 contrast, at Lamasquère, the mean slope for LE was 0.99, and the mean bias was -2.28 W m⁻².
383 However, the mean RMSE for LE at both sites and years was 30.17 W m⁻², which indicates that the
384 model estimated LE correctly. H was slightly overestimated for both sites and both years, with a mean
385 bias of 4.74 W m⁻². This H overestimation arose mostly after harvesting and before ploughing,
386 indicating that the ICARE-SVAT model parameterization for stubble (height and albedo) might be
387 inadequate. However, with an overall mean RMSE of 33.55 W m⁻², the H estimations performed by
388 the ICARE-SVAT model were acceptable. The G estimations were less reliable, with a mean RMSE

389 of 42.52 W m^{-2} and low R^2 and Nash criterion values (0.68 and 0.29, respectively) being determined.
390 Similar results are commonly produced by this kind of model (Olioso et al., 2002). The soil water
391 content simulations integrated from the surface to 150 cm deep (SWC_{0-150}) obtained with ICARE-
392 SVAT were highly accurate, with very low RMSE and mean bias values (both of about 1 %) and
393 elevated R^2 and Nash criterion values (0.83 and 0.80, respectively). An exception to this was observed
394 for Lamasquère in 2007 associated with irrigated maize, when less significant statistical values were
395 obtained (see discussion below), but the ICARE-SVAT simulations were still acceptable. The
396 simulation of the surface soil water content (SWC_{0-5}) was less accurate compare to the SWC_{0-150} , with
397 a RMSE of $0.03 \text{ m}^3 \cdot \text{m}^{-3}$ and a mean Nash value of 0.14 but good R^2 , slopes and bias. It could be
398 explained by the use of the *force-restore* method for water transfer that forced the surface layer to
399 follow the dynamic of the deep-water reservoir. Despite this problem, evaporation is correctly
400 estimated on bare soil due to compensations introduced by surface resistance calibration.

401
402 Comparison of the ICARE-SVAT and MDS results with measurements performed during bare
403 soil periods (Table 1) showed that E was estimated well by both methods (Table 4). The mean R^2 was
404 6 % higher, and the Nash criterion was 11 % higher for ICARE-SVAT than for MDS on average,
405 showing a more scattered prediction for MDS. However, the mean slope was 13% higher, while the
406 mean RMSE was 10% lower for MDS than for ICARE-SVAT. These results show that MDS allowed
407 a realistic and non-biased estimation of E during bare soil periods. Moreover, the estimations of TR
408 produced by MDS and ICARE-SVAT were very similar, with a mean slope for both sites and years of
409 0.99, a mean RMSE of $0.02 \text{ g H}_2\text{O m}^{-2} \text{ s}^{-1}$, a mean R^2 of 0.79 and a Nash criterion value of 0.72.

410 The cumulative E dynamics estimated by MDS (E_{MDS}) and ICARE-SVAT (E_{ICARE}) were in
411 good agreement (Figure 3). In June 2006, at the end of winter wheat development at Auradé, drying of
412 the surface evaporative layer induced high soil resistance to E (Equation 9), which led to lower values
413 of accumulated E_{ICARE} compared to E_{MDS} . For winter wheat at Lamasquère in 2007, E_{ICARE} was lower
414 than E_{MDS} because of the impact of dew simulated by the model (negative E values). In the ICARE-
415 SVAT model, this phenomenon appeared in May 2007, corresponding to a period of colder
416 temperatures, high precipitation and elevated soil water content (Figure 2). Although this phenomenon
417 is plausible, its importance seemed to be too high, as confirmed by the slight underestimation of ETR
418 by ICARE-SVAT. Both the phenomena of excessive drying and dew formation could be explained by
419 the "force-restore" water and temperature dynamics (Gentine et al. 2007, 2011). This soil
420 representation induces strong water exchange between the evaporative surface layer and the root
421 absorption layer. During periods without precipitation the soil surface layer drying resulted in a
422 significantly reduced E, as observed for Auradé winter wheat. For winter wheat at Lamasquère,
423 because of the high precipitation during spring 2007, the modeled surface evaporative layer was
424 always water saturated. This induced low soil surface temperatures (the mean daily modeled soil
425 surface temperatures were $1.7 \text{ }^\circ\text{C}$ lower on average than the temperature measured 10 cm deep

426 between April and June 2007) and dew deposition instead of E (31% of E_{ICARE} data were negative
427 between April and June 2007). The difference between the E estimations from ICARE-SVAT and
428 MDS at Auradé in 2007 corresponds to an overestimation of ETR by ICARE-SVAT compared to the
429 observed ETR, which arose before the full development of the crop and before high TR values were
430 observed. Therefore, the overestimation of R_n by ICARE-SVAT noted above (see Table 3) was
431 probably the main cause of the overestimation of ETR and E by ICARE-SVAT compared to the
432 observed values and to E_{MDS} .

433 On both a seasonal and annual basis, the ICARE-SVAT and MDS partitioning between E and
434 TR were quite comparable (Table 6). The mean absolute difference between the E estimation methods
435 was 24 mm on the seasonal time scale and 30 mm on the annual time scale. These differences can be
436 considered to represent an estimation of the uncertainty of the MDS method. The greater differences
437 observed for winter wheat at Auradé and Lamasquère were the result of particular meteorological
438 conditions and phenomena that the ICARE-SVAT simulation failed to describe, as explained above.
439 However, this did not induce an additional systematic error in MDS partitioning, even though such an
440 error could have been introduced, as both methods were calibrated during bare soil periods and applied
441 during vegetation periods. Radiative transfer, soil temperature and SWC dynamics were taken into
442 account in both cases, but differences in soil texture induced by tillage and progressive ground
443 collapse between sowing and harvesting were not considered. Soil properties and E might have been
444 impacted by these changes.

445 Additional and more comprehensive analyses of the uncertainties and processes involved in
446 these two partitioning methods would require accurate separate measurements of E and TR, which are
447 currently almost impossible. Sap flow measurements only represent one plant and the magnitude of
448 the flow can hardly be compared to the total transpiration. In addition sap flow measurements can be
449 delayed because of the internal water storage within the plant (Goldstein et al. 1998).

450 3.3. Water budget distribution, component dynamics and drivers

451 Mean annual precipitation is 615 mm at Lamasquère and 684 mm at Auradé (Table 5).
452 Precipitation was low during maize development, which was partly compensated for by irrigation.
453 Negative and positive values of ΔSWC_{0-100} were observed, representing soil water reserve increases
454 and decreases, respectively, during the considered period.

455 ETR represented 78 % of the available water $P (+I) - \Delta\text{SWC}$; (see Equation 13) on average on
456 annual time scale. On seasonal time scale, ETR was very similar for all crops, with absolute values
457 ranging between 350 and 400 mm. ETR represented 76% of available water during the growing season
458 for winter wheat, 81% for sunflower and 105% for maize on average. This difference between winter
459 and summer crops was the result of lower water inputs for summer crops than for winter crops during

460 their respective growing seasons, even when considering irrigation. R_n was also higher during
461 summer, which led to higher potential evaporative demands and water absorption by the plant cover.
462 For winter wheat, the seasonal ETR was comparable to that reported by Qiu et al. (2008), ranging
463 between 257.3 and 467.5 mm depending on the irrigation supply. In a study performed by Suyker and
464 Verma (2009), higher ETR values were observed for summer crops on a seasonal time scale, ranging
465 between 431 mm for rainfed soybeans to 548 mm for irrigated maize. These higher values resulted
466 from higher water inputs and higher LAI values for their crops.

467 Although the amounts of annual precipitation are higher at Auradé, estimations of drainage
468 plus runoff water losses represented 26% of the apparent annual water availability, compared to only
469 18% at Lamasquère (Figure 4a). This higher value at Auradé is consistent with the slight slope of this
470 site. The slope might have increased the runoff term during high precipitation events compared to
471 Lamasquère. On seasonal time scale, $D + R$ was important for winter wheat at Lamasquère (Figure 4b)
472 because of the high precipitation on saturated soil in the spring (Figure 2). The negative value of $D +$
473 R for maize at Lamasquère is an artifact that illustrates the measurement uncertainties for P ,
474 ΔSWC_{0-100} and ETR. It therefore represents a negligible value for water loss through drainage and
475 runoff.

476 Overall, based on annual and seasonal time scales, the absolute values of E and its
477 contribution to ETR were higher at Auradé than at Lamasquère (Figure 4 and Table 5). These results
478 were attributed to the higher accumulated incoming radiation at the soil surface layer at Auradé.
479 Indeed, low LAI values (especially for sunflower, see Table 6) coupled to longer bare soil periods
480 (338 days for Auradé *versus* 277 days for Lamasquère for both years) led to higher RG_s values (see
481 section 2.2) at the Auradé site. The differences in the proportion of E in ETR between the seasonal and
482 annual time scales (Figure 4) were more pronounced for maize because of the longer bare soil periods
483 (the regrowth period observed at Lamasquère at the end of 2005 was excluded from the bare soil
484 periods). In contrast, as expected, the absolute values of TR and its contribution to ETR were always
485 higher at Lamasquère. The lower LAI values for Auradé winter wheat and sunflower compared to
486 Lamasquère winter wheat and maize might also explain the lower TR values for Auradé. Moreover,
487 maize irrigation increased the water input and the water available for TR . On annual time scale,
488 according to site management, longer bare soil periods for summer crops explained the lower
489 proportion of TR in the annual ETR compared to winter wheat. The highest proportion of TR in
490 annual ETR was observed for winter wheat at Lamasquère (48%). Indeed, an exceptionally warm
491 winter (Béziat et al., 2009) caused high LAI values, even early in the growing season (Figure 2), and
492 these values remained higher than $1 \text{ m}^2 \text{ m}^{-2}$ from January to June 2007.

493 In conclusion, the partitioning of ETR between E and TR during vegetation periods was
494 mainly driven by incoming radiation partitioning between soil and vegetation, which directly depends
495 on vegetation density and LAI. The partitioning is primarily driven by the duration of the bare soil
496 period on annual time scale and by the LAI crop development dynamics during growing seasons at

497 both seasonal and annual time scales. This last observation is consistent with the results of a study
498 performed on grasslands reported by Hu et al. (2009), who showed that the ratio of annual E/ETR
499 increased from 51% to 67% with a decrease in the mean LAI from 1.9 to 0.5 $\text{m}^2 \text{m}^{-2}$.

500 4. Conclusions

501 Eddy-covariance allow investigating of long-term dynamics of ETR yet do not directly
502 discriminate between the soil E and vegetation TR contributions. A marginal distribution sampling
503 (MDS) method is here used based on few field data to partition, total ETR in E and TR. MDS results
504 were compared to simulations of the site-calibrated ICARE-SVAT double-source mechanistic model.
505 Both methods showed a consistent ETR partitioning. The great advantage of the MDS method is that it
506 does not require calibration and has very few parameters. Reductionism can help fundamentally
507 improve our understanding of the physical processes and our predictive power, as long as it does not
508 try to oversimplify the physics but attempts at capturing the observed emergent behavior of the
509 physical system (Sivapalan 2003). The MDS method aims at capturing the main processes behind the
510 ETR partitioning. Complex land-surface models insufficiently calibrated against short-term
511 measurements can observe the right ETR over a few days yet along with wrong soil-vegetation water
512 flux partitioning: the right answer for the wrong reasons.

513 With partitioning method, we showed that the water budget partitioning between the different
514 components strongly depends on crop plot management and climate variability. E was shown to
515 represent nearly one-third of the water budget during the growing season and nearly half of the water
516 budget on annual time scale. Consequently changes in agricultural practices should help better
517 mitigate soil water use and improve production efficiency. For instance, water losses through E can be
518 mitigated by reducing the bare soil period and by promoting mulching, intercrop or cover crops. This
519 study has focused on water use yet has not considered other components essential to plant growth such
520 as nutrients. Use of intercrop or cover crops should be carefully considered as they would increase TR
521 and could limit the development of the subsequent crop due to mobilizing available nitrogen. The
522 effect of nutrients will be evaluated in future work.

523

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536

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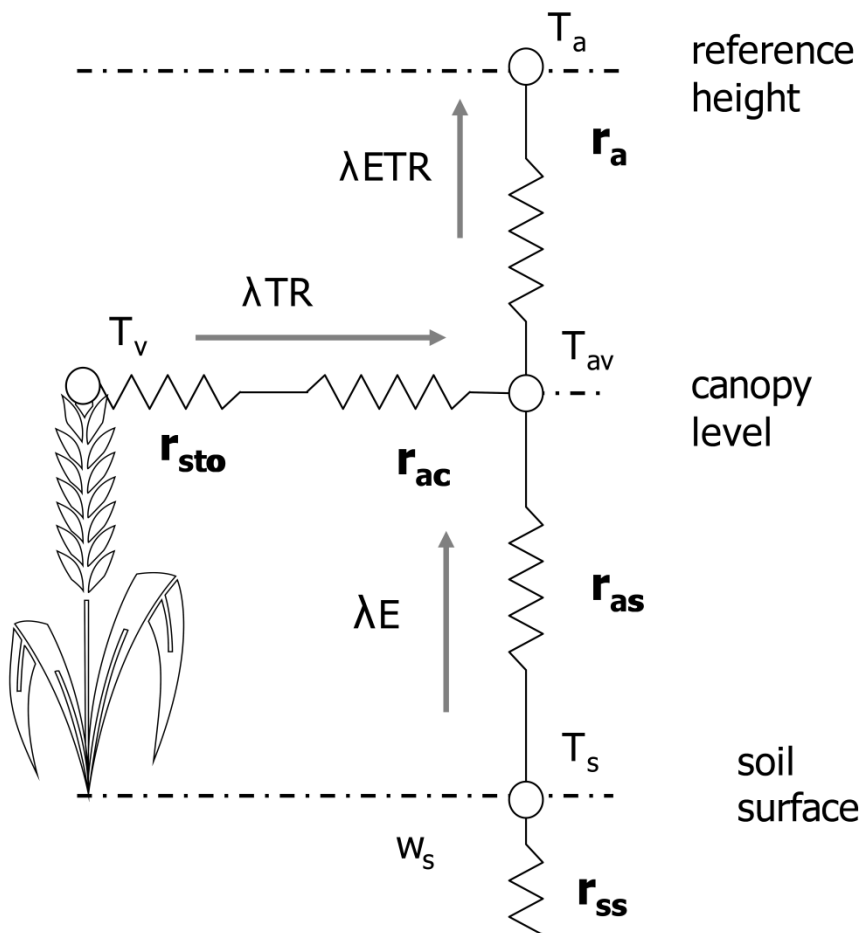
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1 Figures Captions

2

3 **Figure 1: Schematic representation of energy partitioning with the ICARE model. λETR is the latent heat flux (evapotranspiration) composed of λTR (transpiration) from vegetation and λE (evaporation) from soil.**

5

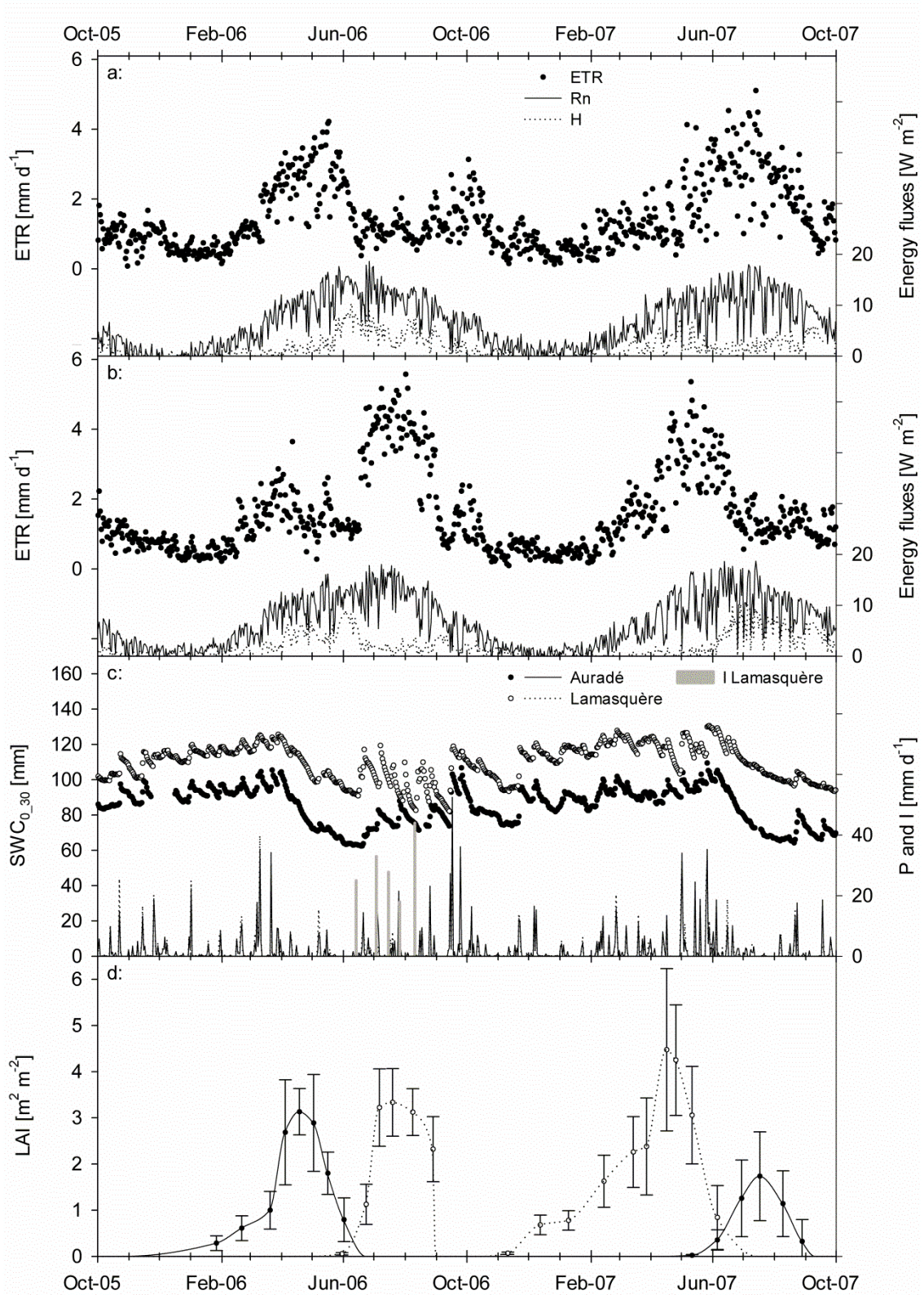


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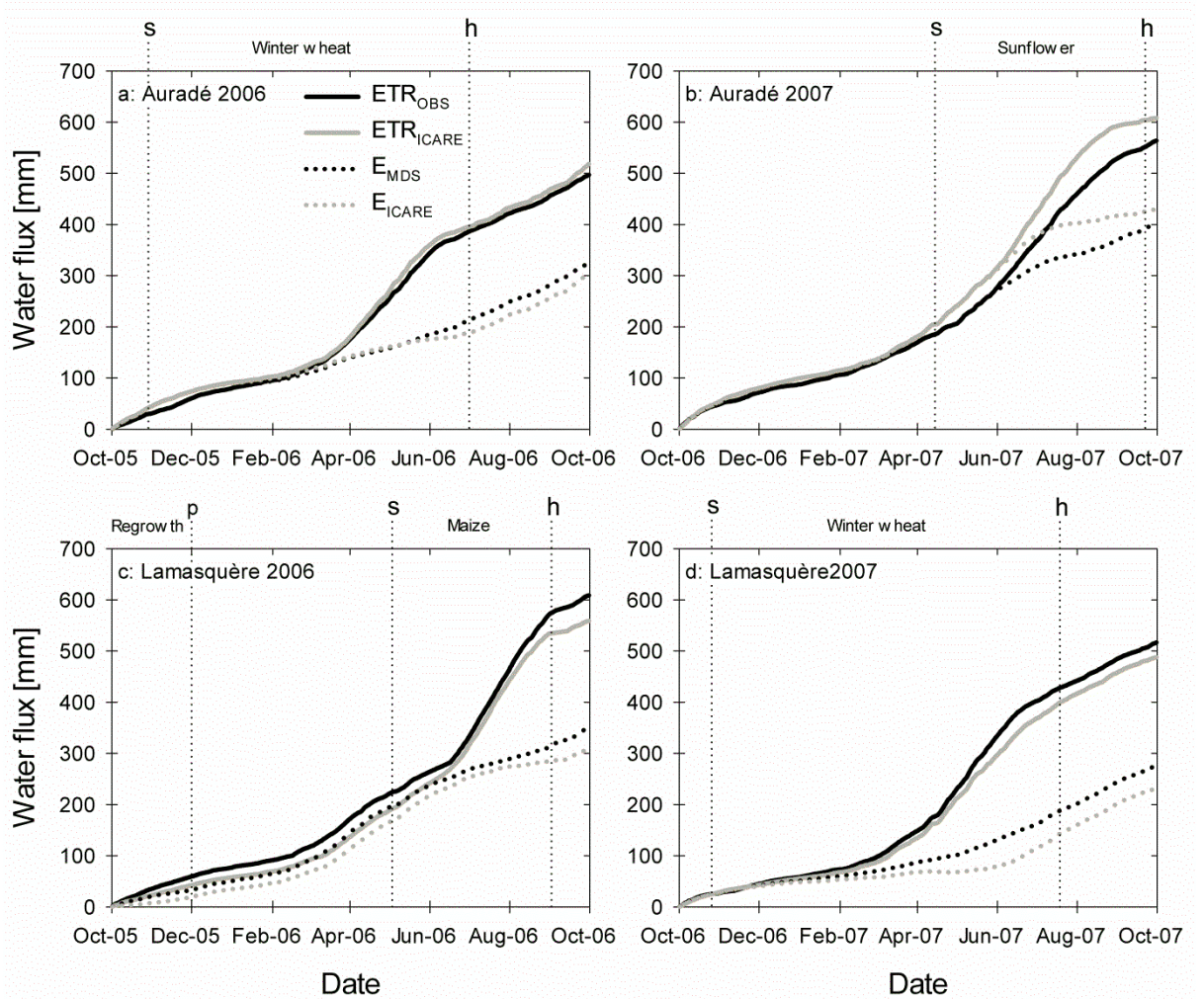
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1 **Figure 2: Seasonal dynamics of the daily evapotranspiration (ETR), net radiation (R_n) and sensible heat**
 2 **flux (H) at Auradé (a) and Lamasquère (b). (c) Daily soil water content between 0 and 30 cm deep**
 3 **($SWC_{0,30}$, open and full circles), daily precipitation at both sites and irrigation at Lamasquère (P, solid**
 4 **and dotted lines and I, gray bars, respectively). (d) Observed leaf area index (LAI, open and full circles)**
 5 **and interpolated LAI (solid and dotted lines) from October 2005 to October 2007. In (d), the error bars**
 6 **correspond to \pm one standard deviation of the mean.**



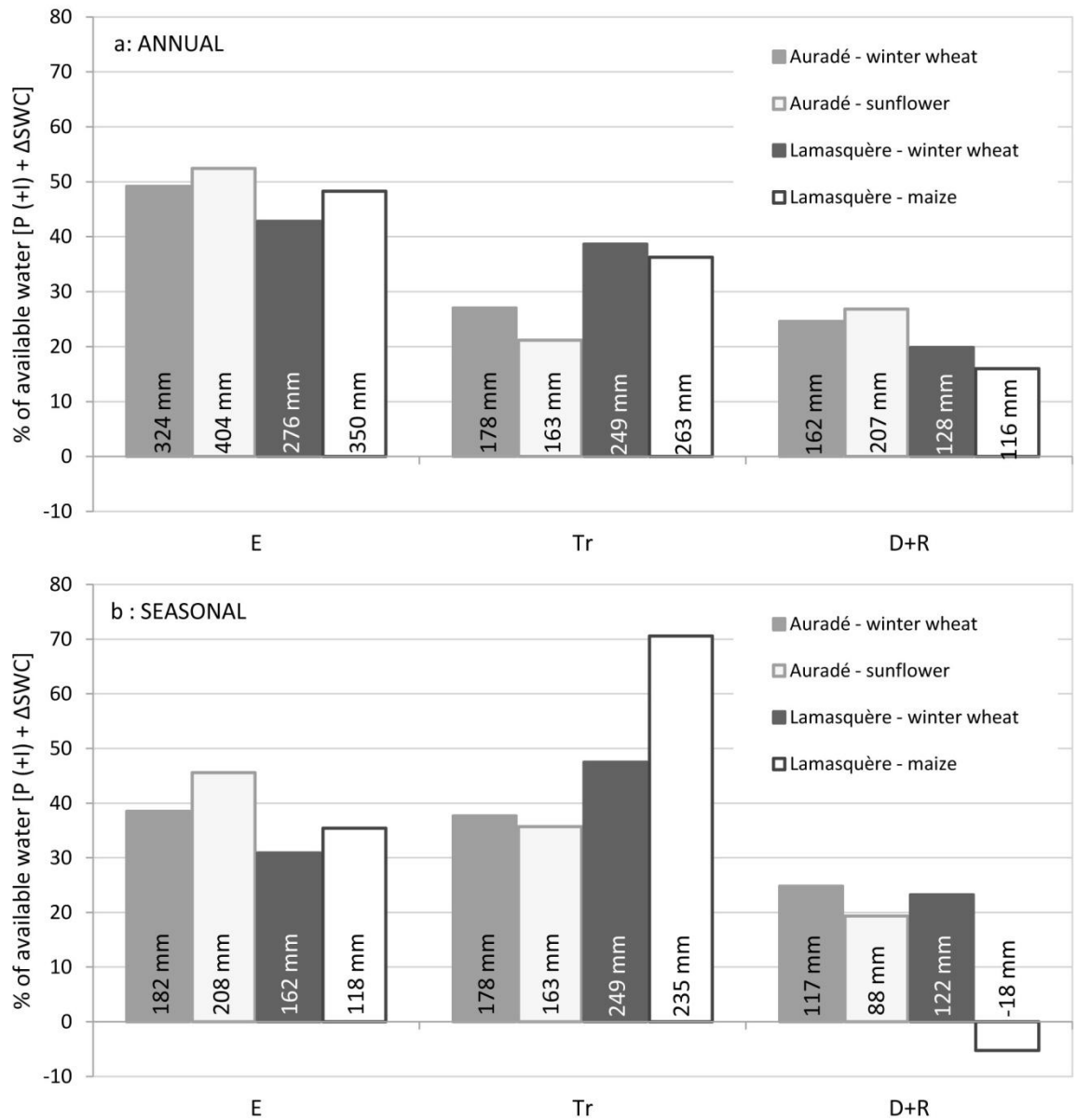
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Figure 3: Comparison of cumulative evapotranspiration (ETR) measured by EC (ETR_{OBS}) and simulated with the ICARE-SVAT model (ETR_{ICARE}) and soil evaporation (E) calculated with the marginal distribution sampling method (E_{MDS}) and with the ICARE-SVAT model (E_{ICARE}) for both sites and both years. Annotations indicate dates of sowing (s), harvesting (h) and ploughing (p) and the name of the crop (or regrowth event).



7
8

1 **Figure 4: Estimation of the seasonal and annual contribution of transpiration (Tr), evaporation (E) and**
 2 **drainage + runoff (D + R) to water losses at the Auradé and Lamasquère sites.**



3

4

1 **Table 1: Bare soil periods and corresponding number of available filtered half-hourly evapotranspiration (ETR) measurements.**

2

Site	Start date	Technical operation	End date	Event/ technical operation	Number of ETR measurements
Auradé	4 July 2005	disking	8 July 2005	re-growth	150
	4 August 2005	disking	28 August 2005	re-growth	889
	23 September 2005	ploughing	27 October 2005	Winter wheat seeding	1192
	30 September 2006	ploughing	10 April 2007	sunflower seeding	5571
	20 September 2007	ploughing	1 st October 2007	end of the dataset	305
					8107 (total)
Lamasquère	11 July 2005	disking	27 August 2005	re-growth	1780
	1 st December 2005	ploughing	1 st May 2006	maize seeding	4137
	31 August 2006	disking	18 October 2006	Winter wheat seeding	1268
					7185 (total)

3

1 **Table 2: Best fit parameters from the ICARE-SVAT model resistance optimisation (see text for details)**
 2 **for Auradé and Lamasquère and for each crop. Global simulation parameters and bare soil parameters**
 3 **for the comparison with the marginal distribution sampling method are reported.**

Parameter	Auradé		Lamasquère	
	Winter wheat	Sunflowers	Maize	Winter wheat
$A_{r_{ss}} \text{ (global) [ln(s m}^{-1}\text{)]}$		21		38
$Z_0/Z_{0h} \text{ (global) [dimensionless]}$		5		37*
$A_{r_{ss}} \text{ (bare soil) [ln(s m}^{-1}\text{)]}$		20		43
$Z_0/Z_{0h} \text{ (bare soil) [dimensionless]}$		6		65*
$SWC_{wilt} \text{ [m}^3 \text{ m}^{-3}\text{]}$	0.08	0.08	0.08	0.2
$r_{smin} \text{ [s m}^{-1}\text{]}$	75	66	130	48

5 * Z_0/Z_{0h} values obtained for Lamasquère site are high values according to literature, but are
 6 resulting of a global optimization process with an absolute minimum convergence.

7

1 **Table 3: ICARE-SVAT model evaluation for energy budget variables (net radiation (Rn), latent heat flux**
 2 **(LE), sensible heat flux (H) and soil heat flux (G)) and for surface and deep soil water content (SWC_{0,5},**
 3 **SWC_{0,150}) integrated over 0 to 5 and 0 to 150 cm down.**
 4

	Slope	Intercept	R ²	RMSE	Mean bias	Nash	n
Auradé							
2005-2006							
Rn [W m ⁻²]	0.99	2.97	0.97	31.52	2.19	0.97	15535
LE [W m ⁻²]	1.11	-2.36	0.88	26.78	2.73	0.82	10948
H [W m ⁻²]	0.86	7.27	0.77	36.36	3.77	0.76	12733
G [W m ⁻²]	1.13	3.07	0.63	45.43	3.20	0.24	15707
SWC _{0,5} [m ³ m ⁻³]	0.85	0.06	0.68	0.03	0.02	0.39	15706
SWC _{0,150} [m ³ m ⁻³]	0.86	0.04	0.92	0.01	0.00	0.92	15707
2006-2007							
Rn [W m ⁻²]	1.04	6.87	0.98	26.00	9.15	0.98	15936
LE [W m ⁻²]	1.08	0.77	0.80	37.91	4.64	0.70	11164
H [W m ⁻²]	0.98	8.16	0.66	38.02	7.91	0.48	12776
G [W m ⁻²]	1.00	0.63	0.68	36.29	0.63	0.54	17161
SWC _{0,5} [m ³ m ⁻³]	0.74	0.10	0.54	0.05	0.04	0.00	17211
SWC _{0,150} [m ³ m ⁻³]	0.89	0.03	0.85	0.01	0.00	0.85	17161
Lamasquère							
2005-2006							
Rn [W m ⁻²]	1.00	-7.20	0.99	19.11	-7.37	0.99	16739
LE [W m ⁻²]	0.96	-1.26	0.88	29.34	-3.74	0.87	10250
H [W m ⁻²]	0.69	10.81	0.75	29.24	4.29	0.74	11809
G [W m ⁻²]	1.24	-0.29	0.70	49.62	0.16	0.28	17151
SWC _{0,5} [m ³ m ⁻³]	0.46	0.21	0.71	0.03	0.02	0.21	17150
SWC _{0,150} [m ³ m ⁻³]	0.94	0.03	0.72	0.02	0.00	0.64	17151
2006-2007							
Rn [W m ⁻²]	0.99	1.25	0.97	25.78	0.84	0.97	17118
LE [W m ⁻²]	1.01	-1.56	0.88	26.67	-0.82	0.86	11567
H [W m ⁻²]	0.71	10.93	0.85	30.59	2.98	0.83	13397
G [W m ⁻²]	1.37	8.83	0.72	38.73	6.84	0.11	17409
SWC _{0,5} [m ³ m ⁻³]	0.62	0.26	0.29	0.04	0.02	0.13	17459
SWC _{0,150} [m ³ m ⁻³]	0.61	0.16	0.66	0.01	0.01	0.50	17409

Table 4: Comparison of ETR measurements during bare soil periods with soil evaporation (E) prediction of the marginal distribution sampling method (MDS) and of the ICARE-SVAT model and comparison of transpiration (TR) estimated by both approaches over both years of experiment. Bare soil corresponds to the validation bare soil dataset (see section 2.4).

	Dataset	Slope	Intercept g H ₂ O m ⁻² s ⁻¹	R ²	RMSE g H ₂ O m ⁻² s ⁻¹	Mean bias g H ₂ O m ⁻² s ⁻¹	Nash	n
Auradé								
E _{ICARE} vs. ETR	bare soil validation	0.71	0.003	0.76	0.012	-0.0020	0.75	3412
E _{MDS} vs. ETR	bare soil validation	0.97	-0.001	0.66	0.012	-0.0018	0.50	3395
TR _{ICARE} vs. TR _{MDS}	2005-2006	1.16	-0.001	0.84	0.014	0.0033	0.71	3681
TR _{ICARE} vs. TR _{MDS}	2006-2007	0.88	0.006	0.64	0.019	0.0019	0.55	2730
Lamasquère								
E _{ICARE} vs. ETR	bare soil validation	1.03	0.005	0.74	0.012	0.0050	0.54	2707
E _{MDS} vs. ETR	bare soil validation	1.03	-0.002	0.76	0.010	-0.0011	0.67	2679
TR _{ICARE} vs. TR _{MDS}	2005-2006	0.88	0.002	0.82	0.018	-0.0027	0.81	3628
TR _{ICARE} vs. TR _{MDS}	2006-2007	1.04	0.000	0.84	0.015	0.0011	0.80	4708

Table 5: Seasonal and annual cumulative values of precipitation and irrigation (P + (I)), soil water content variation integrated over 0 to 100 cm deep (ΔSWC_{0-100}), evapotranspiration observations (ETR_{OBS}) and estimations of the drainage + runoff term (D + R) at Auradé and Lamasquère

	P (+I) [mm]	ΔSWC_{0-100} [mm]	ETR_{OBS} [mm] [% of P (+I) - ΔSWC]		D + R [mm] [% of P (+I) - ΔSWC]	
Auradé						
winter wheat	397	-75	355	75	117	25
sunflower	374	-82	368	81	88	19
2005-2006	684	25	497	75	162	25
2006-2007	671	-100	564	73	207	27
Lamasquère						
maize	145 (+148)	-40	351	105	-18	-5
winter wheat	531	7	403	77	122	23
2005-2006	620 (+148)	43	609	84	116	16
2006-2007	615	-30	517	80	128	20

Table 6: Seasonal and annual cumulative values of observed ETR (ETR_{OBS}) and ETR simulated by the ICARE-SVAT model (ETR_{ICARE}), soil evaporation calculated with the marginal distribution sampling method (E_{MDS}) and by the ICARE-SVAT model (E_{ICARE}), and transpiration calculated with MDS (TR_{MDS}) and the ICARE-SVAT model (TR_{ICARE}) at Auradé and Lamasquère.

	ETR_{OBS}	ETR_{ICARE}	E_{MDS}		E_{ICARE}	TR_{MDS}		TR_{ICARE}
	[mm]	[mm]	[mm]	[% of ETR_{OBS}]	[mm]	[mm]	[% of ETR_{OBS}]	[mm]
Auradé								
winter wheat	355	355	182	51	148	178	50	207
sunflower	368	403	208	57	224	163	44	179
2005-2006	497	518	324	65	307	178	36	212
2006-2007	564	608	404	72	429	163	29	179
Lamasquère								
maize	351	345	118	34	119	235	67	225
winter wheat	403	374	162	40	117	249	62	256
2005-2006	609	559	350	57	308	263	43	251
2006-2007	517	488	276	53	231	249	48	256