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Implementing a new texture-based soil evaporation reduction coefficient in the FAO-2Kc method

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Abstract

Crop evapotranspiration (ET) is a fundamental component of the hydrological cycle, especially in arid/semi-arid regions. The FAO-56 offers an operational method for deriving ET from the reduction (dual crop coefficient K_c) of the atmospheric evaporative demand (ET_0). The dual coefficient approach (FAO-2Kc) is intended to improve the daily estimation of ET by separating the contribution of bare soil evaporation (E) and crop transpiration components. The FAO-2Kc has been a well-known reference for the operational monitoring of crop water needs. However, its performance for estimating the water use efficiency is limited by uncertainties in the modeled evaporation/transpiration partitioning. This paper aims at improving the soil module of the FAO-2Kc by modifying the E reduction coefficient (K_r) according to soil texture information and state-of-the-art formulations, hence, to amend the mismatch between FAO-2Kc and field-measured data beyond standard conditions. In practice this work evaluates the performance of two evaporation models, using the classical K_r ($K_{r,FAO}$) and a new texture-based K_r ($K_{r,text}$) over 33 bare soil sites under different evaporative demand and soil conditions. An offline validation is investigated by forcing both models with

32 observed soil moisture (θ_s) data as input. The $K_{r,\text{text}}$ methodology provides more accurate E
33 estimations compared to the $K_{r,\text{FAO}}$ method and systematically reduces biases. Using
34 $K_{r,\text{text}}$ allows reaching the lowest root means square error (RMSE) of 0.16 mm/day compared
35 to the $K_{r,\text{FAO}}$ where the lowest RMSE reached is 0.88 mm/day. As a step further in the
36 assessment of the proposed methodology, ET was estimated in three wheat fields across the
37 entire agricultural season. Both approaches were thus inter-compared in terms of ET estimates
38 forced by SM estimated as a residual of the water balance model (online validation).
39 Compared to ET measurements, the new formulation provided more accurate results. The
40 RMSE was 0.66 mm/day (0.71 mm/day) and the R^2 was 0.83 (0.78) for the texture-based
41 (classical) Kr.

42 *Keywords: FAO-2Kc, soil evaporation, soil texture, soil moisture, evapotranspiration.*

43 **1. Introduction**

44 Surface evapotranspiration (ET) is an important flux in water and energy exchange processes
45 at the interface between land surfaces and the atmosphere. Soil evaporation (E) is one of the
46 main components of ET beside plant transpiration. E accounts for a substantial part of ET
47 from the exposed soil surface in growing crops, where its spatial distribution plays an
48 important role in various fields such as hydrology, meteorology and agronomy. In addition, E
49 is the only hydrological flow that connects both water (through soil moisture) and energy
50 (through land surface temperature) balances. About 50 % to 70 % of annual precipitation is
51 consumed by E to the atmosphere which is considered as a water loss and not used for crop
52 productivity (Harrold et al., 1959; Peters, 1960; Wallace, 2000).

53 Partitioning ET is essential in modeling land atmosphere interactions and vegetation water
54 uptake and it is crucial in the monitoring of plant water uptake and water stress (Er-raki et al.,
55 2010; Merlin et al., 2016; Porporato et al., 2001; Rafi et al., 2019). In agricultural crops, water
56 is mainly lost by E during the germination and emergence stage of growing crops. Then,
57 through the crop growth and development, the surface is covered; therefore, E impacts less
58 the water change in the soil while the transpiration becomes the main process and dominates
59 ET. In arid and semi-arid regions including irrigated areas, E is the main outward flux and
60 influences the soil water budget, which is very vital for agriculture (Suleiman and Ritchie,
61 2003). Schlesinger and Jasechko, (2014) reported that the E contribution into ET ranges from
62 20 % to 40 %, and it is an essential boundary condition between soil and atmosphere.

63 It is well known that the E process occurs in two main stages. The first stage is characterized
64 by a constant rate of E which is also known as the energy-limited stage. It corresponds to
65 when the evaporation occurs at a maximum rate meaning that it is limited only by the external
66 meteorological (radiation, wind speed and relative humidity) conditions. This stage continues
67 as long as the soil underneath has enough water storage. The second stage, also named the
68 falling rate stage, corresponds to when the surface dries so that the evaporation becomes
69 limited by soil moisture (θ_s) and by the soil hydraulic properties that determine the transfer of
70 liquid and vaporized water to the surface. In this stage the soil resistance to water diffusion
71 increases until θ_s reaches its minimal value (Chanzy et al., 1993). The rate of evaporation and
72 the duration of both stages vary with soil texture. Therefore, more water can be evaporated
73 from saturated clayey soil than from saturated sandy soils because more water is stored in a
74 clayey soil than in a sandy soil.

75 Different techniques have been used to measure E. Among them, we cite weighing lysimetry
76 (Balwinder-Singh et al., 2011; Boast and Robertson, 1982; Leuning et al., 1994), isotopy
77 (Aouade et al., 2016; Zhang et al., 2011) and portable evaporation chamber (Luo et al., 2018;
78 Raz-Yaseef et al., 2010). Recently, Rafi et al. (2019) intercompared different methods based
79 on eddy covariance, sap flow and weighing lysimetry measurements to assess E. The above
80 techniques provided E measurements at a crop field scale.

81 The FAO dual crop coefficient model (FAO-2Kc, Allen, 2000) is one of the most widely used
82 models to estimate crop ET due to its simplicity and operationality, and it has been applied in
83 standard and beyond standard conditions (Suleiman et al., 2007). The FAO-2Kc consists in
84 splitting the crop coefficient K_c into two separate coefficients, one for crop transpiration,
85 called the basal crop coefficient (K_{cb}) and one for soil evaporation (K_e). FAO-2Kc model
86 requires limited input parameters and it has been used to simulate ET of crops like wheat
87 (Drerup et al., 2017; Er-raki et al., 2010; Er-Raki et al., 2007; Jin et al., 2017), olive (Er-raki
88 et al., 2008; Er-Raki et al., 2010), citrus (Rallo et al., 2017), table grapes (Er-Raki et al.,
89 2013), sugar beet (Anderson et al., 2017; Diarra et al., 2017) crops grown under different
90 climates (Ayyoub et al., 2017; Debnath et al., 2015).

91 Despite the numerous applications of FAO-2Kc, many studies reported that the E component
92 is not well quantified. In some studies, the FAO-2Kc method overestimates E at the start of
93 the season and underestimates it at the end of the season (Mutziger et al., 2005; Parlange et
94 al., 1992; Torres and Calera, 2010). Rafi et al., (2019) and Olivera-Guerra et al., (2018) found
95 an underestimation of E at the start and the end of the wheat growing season. This is

96 potentially due to the classical K_e or more specifically to the reduction coefficient K_r of FAO-
97 2Kc which is based on an ad hoc relationship with texture via the θ_s at field capacity (Merlin
98 et al., 2016). Moreover, Phillips et al., (2017) stated that most land-surface models used to
99 estimate E cannot differentiate soil texture and this is due to the difficulty to incorporate the
100 soil texture effect on the E rate.

101 Merlin et al., (2016) showed that the nonlinear relationship between E rate and surface θ_s over
102 bare soils varied systematically with soil texture across several well-instrumented sites. Based
103 on this work, a new K_r formula was proposed based on the soil texture information using a
104 new pedo-transfer function that physically links K_r to texture ($K_{r,\text{text}}$). The new pedo-transfer
105 function was developed in Merlin et al. (2016) using a meta-analysis approach and was
106 recently corroborated by a physically-based modelling approach relying on soil
107 hydrodynamical properties to simulate capillary flow (Lehmann et al. 2018). This gives
108 independent insight and additional confidence on the robustness of the proposed pedo-transfer
109 function.

110 The aim of the study is therefore to assess the usefulness of the pedo-transfer function of
111 Merlin et al. (2016) within the FAO formalism using - for the first time - 36 contrasted sites.
112 First, the new ($K_{r,\text{text}}$) and classical ($K_{r,\text{FAO}}$) formulations are tested over 33 bare (or
113 approximately bare) soil sites with different soil textures and compared against E
114 measurements. In this case, *in situ* soil moisture data are used as forcing (offline validation),
115 by considering the evaporation module separately from the water budget model, meaning that
116 the soil moisture forcing of K_r is measured. Note that among the 33 bare sites used to evaluate
117 the FAO evaporation estimates in the offline mode, 32 sites belong to the calibration data set
118 of Merlin et al. (2016) while the remaining site (MOBou) is used in this paper for the
119 evaluation. Then, as a complementary assessment of the new evaporation formulation, crop
120 ET was retrieved during the entire agricultural season. In this case, the simulated soil moisture
121 (θ_{FAO}) is used as forcing to $K_{r,\text{FAO}}$ and $K_{r,\text{text}}$ (online validation) by considering the evaporation
122 module coupled to the water budget model, meaning that the soil moisture forcing of K_r is
123 simulated by the FAO water budget model. Both formulations of soil evaporation were
124 evaluated in terms of total ET estimates over three wheat sites located in Morocco near
125 Marrakech. Note that the 3 wheat sites (B123, EC1, EC2) was used in this paper to validate
126 the online implementation of the soil evaporation reduction coefficient in the FAO model. All
127 the three sites do not belong to the calibration data set of Merlin et al. (2016).

128 2. Sites and data description

129 In this study, a significant number of sites (33 bare soil and 3 wheat sites) have been used and
 130 divided into two categories depending on the desired objectives: i) the 33 bare soil sites have
 131 been used for comparing $K_{r,FAO}$ and $K_{r,ext}$ under bare soil conditions only, and ii) the 3 wheat
 132 plots have been used to evaluate the new evaporation module when coupled to the crop water
 133 budget during the entire growing season including all phenological stages of wheat. A
 134 description of all the sites is presented below. More details about all the 32 bare soil sites but
 135 MOBou can be found in [Merlin et al. \(2016\)](#).

136 The studied 33 bare soil sites were differing in climatic conditions and soil textures (Table 1).
 137 These sites are situated in 13 countries all over the world among which 8 are located over
 138 uncropped lands, containing the natural lands including sand desert (NIHAP), savanna fallow
 139 (NISav) and degraded land (NIDeg), native grass (AUStu), grass for silage or hay (USDk1),
 140 short grass following fireforest (USFwf), and sparse shrub (USMo1 and USMo7). The
 141 remaining 25 sites are located over agricultural fields where an identification of bare soil
 142 periods is performed. In this study, “bare soil” period is defined as a time period when the
 143 plant transpiration is either negligible or small compared to E. Hence the term “bare soil”
 144 includes both actual bare soil conditions, and soils partially covered by mulch, crop residue,
 145 or sparse vegetation. The data were collected from several national and international flux
 146 station networks, intensive field measurements and extracted during bare or quasi bare soil
 147 periods by [Merlin et al. \(2016\)](#). Table 1 indicates the localization of the different 33 bare soil
 148 sites, where most sites are located in Europe continent. In Table 1, the clay and sand fractions
 149 are presented. The sand fraction ranges from 0.05-0.92 and clay fraction from 0.02-0.56. Such
 150 a wide observation range of sand and clay fraction allows for testing the methodologies over
 151 different soils. Additional soil physical properties are also given in Table 1 such as, the
 152 volumetric soil moisture at saturation (θ_{SAT}), soil moisture at field capacity (θ_{FC}) and soil
 153 moisture at wilting point (θ_{WP}) as well as the readily evaporable water (REW). These
 154 parameter values are estimated with pedotransfer functions based on clay and sand fractions
 155 ([Brisson and Perrier, 1991](#); [Cosby et al., 1984](#); [Noilhan et al., 1996](#)).

156 *Table 1: Study sites and their soil physical properties.*

Sites	Sand (%)	Clay (%)	θ_{SAT} (m^3/m^3)	θ_{WP} (m^3/m^3)	θ_{FC} (m^3/m^3)	REW (mm)	Country
AUStu	34.3	14.5	0.4079	0.205	0.335	9.5	Australia
BELon	7.5	20	0.4566	0.205	0.335	9.5	Belgium
CHOe2	9.5	43	0.4940	0.23	0.36	10	Switzerland
DEGeb	9.5	30	0.467	0.205	0.335	9.5	Germany
DEKli	21.5	55.7	0.4798	0.22	0.36	10	Germany

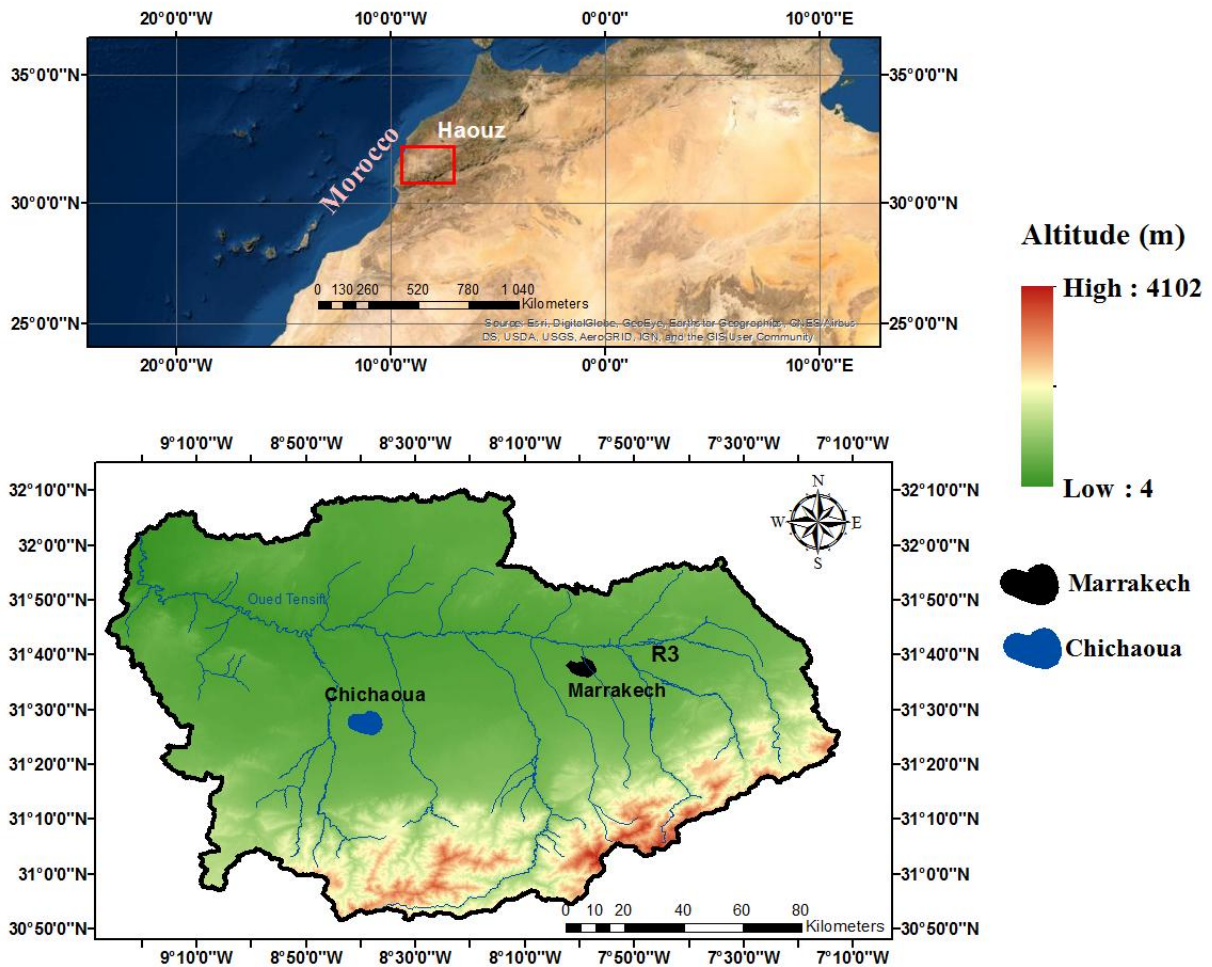
DESeh	16.8	12.2	0.4465	0.205	0.335	9.5	Germany
DKVou	92	2	0.3816	0.045	0.12	4.5	Denmark
ESES2	10.4	47.5	0.4963	0.23	0.36	10	Spain
FRAur	20.6	32.3	0.4570	0.205	0.335	9.5	France
FRAvi	13.2	32.8	0.4691	0.205	0.335	9.5	France
FRGri	9.8	18.9	0.4522	0.205	0.335	9.5	France
FRLam	12	54.3	0.4984	0.22	0.36	10	France
FRRE1	5	40	0.4979	0.205	0.335	9.5	France
FRRE2	5	40	0.4979	0.205	0.335	9.5	France
IECa1	57	17	0.3893	0.11	0.23	8	Ireland
ITBCi	32	46	0.4491	0.22	0.36	10	Italy
ITCas	25	22	0.4274	0.15	0.29	9.5	Italy
MEYaq	36	44	0.4387	0.22	0.36	10	Mexico
MOBou	41	18	0.4373	0.15	0.244	8	Morocco
MOSR1	18.5	47	0.4787	0.22	0.36	10	Morocco
MOSR2	18.5	47	0.4787	0.22	0.36	10	Morocco
NIDeg	77	8	0.3835	0.11	0.23	8	Niger
NIHAP	93	5.7	0.3714	0.045	0.12	4.5	Niger
NIMil	77	8	0.3835	0.11	0.23	8	Niger
NISav	77	8	0.3835	0.11	0.23	8	Niger
USArm	28	43	0.4548	0.22	0.36	10	USA
USDk1	48	9	0.3966	0.12	0.25	9	USA
USFwf	30	13	0.4163	0.15	0.29	9.5	USA
USIb1	10	35	0.4791	0.205	0.335	9.5	USA
USIHO	58	28	0.3886	0.205	0.335	9.5	China
USMo1	66	10	0.3860	0.11	0.23	8	USA
USMo7	80	6	0.3847	0.065	0.15	6	USA
USSGP	26	24	0.4301	0.23	0.36	10	USA

157 In addition to soil texture, continuous measurements of energy fluxes had been monitored in
158 each site such as net radiation (R_n), soil conduction (G) and sensible and latent heat fluxes
159 (H) and (LE), respectively. Measured LE is corrected using the Bowen ratio (Twine et al.,
160 2000). Note that, in some sites LE is missing. In this case, LE is estimated as the residual of
161 the energy balance equation.

162 The three wheat crops used for evaluating E estimations by simulating total ET are located
163 close to Marrakech, Morocco (Figure 1). This region is characterized by a semi-arid to arid
164 climate with high reference ET and low precipitation. Agricultural areas are generally covered
165 by winter wheat crops. The three winter wheat fields are comprised of one flood irrigation
166 plot (B123) of 4 ha located in an irrigated agricultural zone (called R3) and two drip-irrigated
167 fields, both being 1.5 ha and situated in Chichaoua region. Both regions are located in the
168 Haouz plain. The area undergoes contrasted atmospheric conditions all over the year with
169 high temperature and low rainfall (less than 250 mm/ year) during summer and low
170 temperature and irregular rainfall from autumn to spring with a high evaporative demand
171 (1600 mm/year). Wheat is the dominating crop (50 %) of the R3 zone, which is known for its
172 heterogeneity and contains different types of land cover (alfalfa, wheat, olive, orange and

173 horticulture). Numerous studies have been carried out since 2002 on this area ([Ait Hssaine et](#)
174 [al., 2018](#); [Amazirh et al., 2019, 2018, 2017](#); [Chehbouni et al., 2008](#); [Khabba et al., 2013](#); [Ojha](#)
175 [et al., 2019](#); [Olivera-Guerra et al., 2020](#)). The Chichaoua site has been monitored since 2016.
176 Both wheat sites in Chichaoua were sown in November 2016, with the same drip irrigation
177 system. One of the plots (EC1) had been irrigated according to FAO crop water requirements
178 and the other plot (EC2) had undergone stress in controlled conditions. Additional details and
179 information about the study sites can be found in [Amazirh et al. \(2018\)](#), [Merlin et al. \(2018\)](#)
180 [and Rafi et al. \(2019\)](#).

181 During the investigated agricultural seasons, all the three sites were monitored by an eddy
182 covariance system, equipped with different sensors providing continuous measurements of
183 energy and water fluxes exchanged between soil, vegetation and atmosphere. The installed
184 hygrometer provided continuous measurements of H and LE fluxes. Additional instruments
185 were installed in the tower providing extra measurements such as a Sonic 3D anemometer
186 designed to measure the wind speed over the 3 orthogonal axes. R_n was measured by the net
187 radiometer Kipp and Zonen CNR4.



188

189 *Figure 1: Study areas where the coupled approach ($K_{r,ext}$ -FAO-2Kc) is evaluated.*

190 Half-hourly or sub-hourly measurements of classical meteorological data composed of air
 191 temperature T_a , wind speed u_a , incoming solar radiation R_g and air relative humidity rh_a were
 192 collected at a reference height (2 m). Soil moisture data were also measured by Time Domain
 193 Reflectometry sensors over the 3 sites at different soil depths (5, 10, 15, 30, 100 cm). In this
 194 work two surface layers were used: 5 and 10 cm. A mean value between the two layers has
 195 been used to assess soil moisture within the 0-10 cm soil column. For the sites where the soil
 196 moisture at 10 cm is unavailable and only soil moisture at 5 and 15 cm are available, a
 197 linearly interpolation as in [Merlin et al. \(2011\)](#) was used to estimate the integrated soil
 198 moisture from 0 to 10 cm depth.

199 3. Methodologies

200 3.1. Dual crop coefficient method FAO-56

201 [Allen et al. \(1998\)](#) describe with details the theoretical background to assess crop ET. The
 202 FAO-56 method is based on FAO-24 ([Doorembos and Pruitt, 1975](#)), where ET is estimated
 203 based on the crop coefficient (K_c) and the reference evapotranspiration (ET_0). [Allen, \(2000\)](#)
 204 and [Allen et al. \(2005b, 2005a, 1998\)](#) incorporate the dual crop coefficient, splitting K_c into
 205 crop and bare soil contributions. Using the dual crop coefficient method allows for
 206 partitioning ET into bare soil evaporation and plant transpiration beyond standard conditions
 207 using two coefficients: the soil water evaporation coefficient (K_e) to describe E from the soil
 208 surface and the basal crop coefficient (K_{cb}) to describe plant transpiration (Equation 1). The
 209 daily variation in the crop coefficient is a function of the wetness of the soil surface and plant
 210 development. The crop ET under well-watered conditions is written as ([Steduto et al., 2009](#)):

$$211 \quad ET_c = (K_{cb} + K_e)ET_0 \quad (1)$$

212 with ET_c being the maximal crop ET, ET_0 being the ET rate over a well-watered crop land
 213 covered by a short green, grass-like crop (reference ET), depending only on atmospheric
 214 conditions. An adjustment is made to obtain the actual estimates of the real crop ET_a by
 215 introducing the water stress coefficient K_s into the Equation (1), and it becomes:

$$216 \quad ET_a = (K_{cb}K_s + K_e)ET_0 \quad (2)$$

217 In this paper we aim to improve the representation of E in Equation (2). Under bare soil
 218 conditions, crop transpiration is equal to zero ($K_{cb}=0$). E from Equation (3) is expressed as:

$$219 \quad E = K_e ET_0 \quad (3)$$

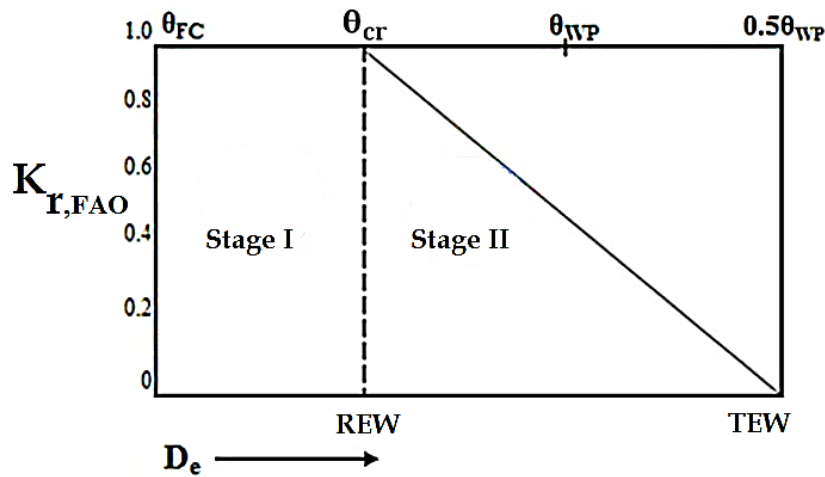
220 Soil evaporative coefficient (K_e) is a function of the amount of water in the soil, soil
 221 properties and the exposed and wetted soil fraction to solar radiation where most E occurs
 222 (f_{ew}). K_e is defined using Eq. 4:

$$223 \quad K_e = \min\{[K_r(K_{cmax} - K_{cb})], [f_{ew}K_{cmax}]\} \quad (4)$$

224 where $f_{ew} = \min(1-fc, fw)$ with fw being the fraction of the soil surface wetted by irrigation
 225 or rainfall (fw is 1 in case rainfall) and fc the fraction of surface covered by vegetation, and
 226 where K_{cmax} is the maximum value (ranging from 1.05 to 1.30) of crop coefficient K_c
 227 following rain or irrigation. It represents the upper limit on E and transpiration that reflects
 228 the natural constraints on available energy. For bare soil, K_{cb} is again equal to 0 and K_{cmax} is
 229 equal to 1.2 ([Allen et al., 2005b, 1998](#)). K_e formula becomes:

230 $K_e = K_{cmax}K_{r,FAO}$ (5)

231 with K_r being the reduction coefficient, which depends on the cumulative depth of water
 232 depleted (D_e) and the amount of water that can be depleted by E during a complete drying
 233 cycle (TEW). Following wetting by precipitation or irrigation, $K_{r,FAO}$ can be as high as 1.
 234 When the soil surface is dry, $K_{r,FAO}$ is small and can even reach zero. E is presumed to take
 235 place in two stages and the reduction coefficient $K_{r,FAO}$ is expressed differently for both stages
 236 (Figure 2): energy is the limiting factor of E during stage I (constant drying rate) and soil
 237 moisture is the limiting factor during stage II (falling drying rate). Stage I begins from $D_e=0$
 238 and holds until D_e is equal to the readily evaporable water (REW) and where the soil moisture
 239 equals to a given critical soil moisture θ_{cr} (value when soil begins to resist to evaporation). In
 240 this stage, the soil surface remains wet and the evaporation rate is controlled by the energy
 241 available at the soil surface. Stage I holds until water cannot be transported to near surface as
 242 fast as the rate to supply the atmospheric demand. Here stage II begins (D_e exceeds REW).



243
 244 *Figure 2: $K_{r,FAO}$ as function of D_e for classical FAO (Allen et al., 1998)*

245 The reduction coefficient decreases and becomes smaller than 1 in proportion to the amount
 246 of water present in the surface soil layer. $K_{r,FAO}$ of Equation (5) is written as:

247
$$K_{r,FAO} = \frac{TEW - D_e}{TEW - REW} \quad ; D_e > REW \quad (6)$$

248
$$K_{r,FAO} = 1 \quad ; D_e < REW$$

249 with REW (mm) depending on soil texture. FAO-56 provides a table for each soil type. REW
 250 normally ranges from 5 to 12 mm and is highest for medium and fine textured soils (Ritchie,
 251 1972; Ritchie et al., 1989). D_e is the cumulative depletion from the soil surface layer by
 252 evaporation (mm). The estimation of D_e requires a daily water balance model of the topsoil

253 layer. Otherwise soil moisture (θ_s) information can be used directly in the D_e calculation as
254 follows.

$$255 \quad D_e = 1000(\theta_{FC} - \theta_s)Z_e \quad (7)$$

256 TEW (mm) is the maximum depth of water evaporated from the surface layer:

$$257 \quad TEW = 1000(\theta_{FC} - 0.5\theta_{WP})Z_e \quad (8)$$

258 where Z_e is the effective depth of soil in which the atmosphere can extract water by E.

259 θ_{FC} , θ_{WP} and REW are reported for each site in table 1 depending on the soil texture
260 classification. For Z_e , FAO-56 recommended a value of 10 cm for coarse soils and 15 cm for
261 fine textured soils (Hanks and Hill, 1980; Ritchie, 1972; Wright, 1982). The values of TEW,
262 Z_e and REW are important factors that control and influence the E process.

263 Step calculation of the classical K_{rFAO} evaporation model is presented in the flowchart (Figure
264 3).

265 **3.2. New texture-based approach**

266 The FAO-56 classical E method (K_{rFAO}) is sensitive to the E depth. Thus, the FAO-2Kc E
267 equation uses a given soil thickness. In the FAO-2Kc, they recommended a value of Z_e of 0.1
268 to 0.15 m which is suitable for the water balance model. Jacquemin and Noilhan. (1990), Lee
269 and Pielke. (1992) and Noilhan and Planton. (1989) proposed a formulation of soil
270 evaporative efficiency based on surface soil moisture and soil moisture at the field capacity in
271 two specific soil thickness layers. Chanzy and Bruckler, (1993), Komatsu. (2003) and Merlin
272 et al. (2016, 2011) found a nonlinear behavior of soil evaporative efficiency as a function of
273 soil moisture.

274 Merlin et al. (2011) proposed an expression of the soil evaporative efficiency for various soil
275 thicknesses based on soil moisture and soil texture information. The reduction coefficient K_r
276 based on soil texture ($K_{r, \text{text}}$) is written as:

$$277 \quad K_{r, \text{text}} = \left[0.5 - 0.5 \cos \left(\frac{\pi \theta_s}{\theta_{\max}} \right) \right]^P ; \theta_s < \theta_{\max} \quad (9)$$

$$278 \quad K_{r, \text{text}} = 1 \quad ; \theta_s > \theta_{\max}$$

279 where θ_s is the surface soil moisture, θ_{\max} is taken equal to soil moisture at saturation θ_{SAT}
 280 by contrast of the work of [Jacquemin and Noilhan. \(1990\)](#) and [Lee and Pielke. \(1992\)](#), and P
 281 is a semi-empirical parameter depending on the soil moisture sensing depth and soil
 282 proprieties (texture).

283 [Merlin et al. \(2016\)](#) proposed an empirical Pedo-transfer (PTF) equation of the critical soil
 284 moisture ($\theta_{1/2}$) at which the actual E rate is half the potential E rate. In practice $\theta_{1/2}$ was
 285 correlated with soil texture (clay and sand content) with a good correlation coefficient (0.6 for
 286 sand fraction and 0.8 for clay fraction). A negative correlation was found between $\theta_{1/2}$ and
 287 sand fraction while it increases as a function of clay fraction. To benefit from the
 288 complementary information on soil water retention capacity, a multilinear regression of
 289 $\theta_{1/2}$ with both sand and clay fractions has been established named as the texture-based PTF. In
 290 this study, the PTF of [Merlin et al. \(2016\)](#), is used to check out its utility within the FAO
 291 formalism. This formulation is tested over 33 study sites to evaluate the FAO evaporation
 292 estimates, with 32 sites belonging to the calibration data set of [Merlin et al. \(2016\)](#) and the
 293 remaining site (MOBou) used as an independent data set for the evaluation of E estimates.
 294 Then, the three additional independent sites (EC1, EC2, B123) are used to assess wheat
 295 surface evapotranspiration. All the three sites were not used in the calibration process in
 296 [Merlin et al. \(2016\)](#).

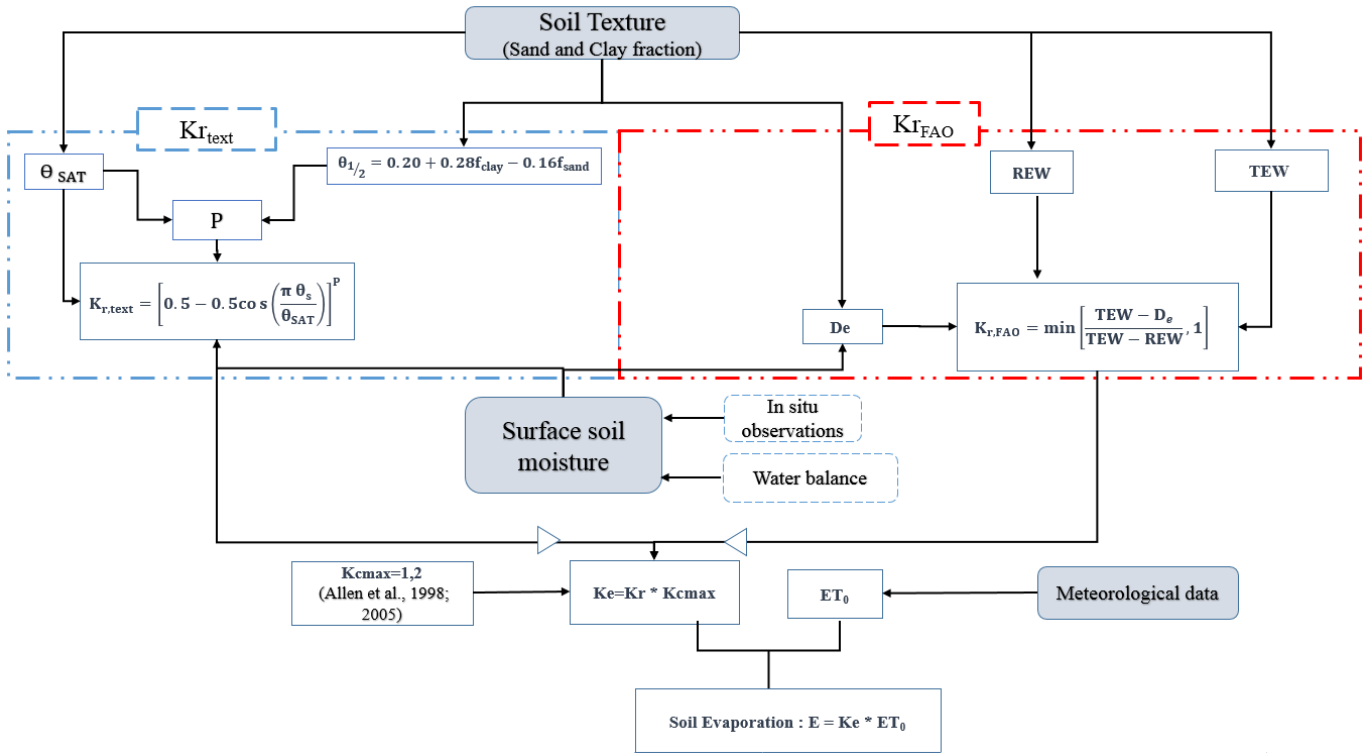
297 $\theta_{1/2}$ is then written as:

$$298 \quad \theta_{1/2} = 0.20 + 0.28f_{\text{clay}} - 0.16f_{\text{sand}} \quad (10)$$

299 The advantage of the Eq 9, is that it can be calibrated using one single parameter P as shown
 300 in [Merlin et al. \(2011\)](#). Indeed, the formulation presented in [Merlin et al. \(2011\)](#) is a
 301 parsimonious formulation well adapted for parameterization with texture information. Hence,
 302 the idea is to parametrize simply $\theta_{1/2}$ presented in Equation (10) as a function of the single
 303 parameter P in which $K_{r,\text{text}}$ is approached linearly at the mid-value ($K_{r,\text{text}}(\theta_{1/2}) = 0.5$).
 304 Therefore, P parameter can be deduced at $\theta_s = \theta_{1/2}$ by inverting Eq 9:

$$305 \quad P = \frac{\ln[K_{r,\text{text}}(\theta_{1/2})]}{\ln\left[0.5 - 0.5 \cos\left(\frac{\pi \theta_{1/2}}{\theta_{\text{SAT}}}\right)\right]} \quad \text{where } K_{r,\text{text}}(\theta_{1/2}) = 0.5 \quad (11)$$

306 The flowchart for E calculation using the new approach is also illustrated in Figure 3.

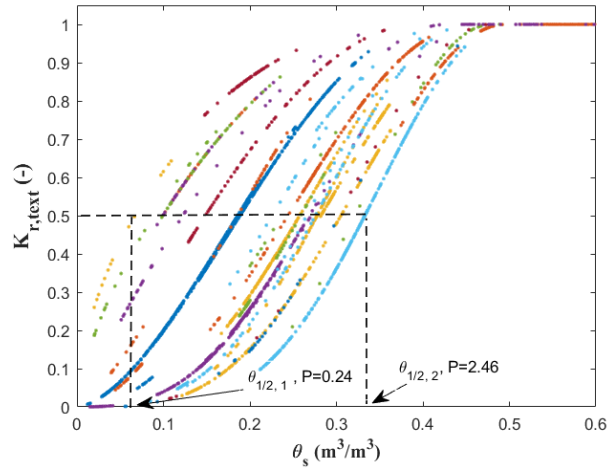


307

308 Figure 3: Flowchart presenting an overview of the main input and output data of the classical
 309 $K_{r,FAO}$ (Em-dashed red rectangle) and the new textural-based approach $K_{r,text}$ (Em-dashed
 310 blue rectangle) to estimate soil evaporation (E).

311 4. Results and discussions

312 Figure 4 plots the texture-based simulated Kr ($K_{r,text}$) as a function of soil moisture at 0-5 cm
 313 depth for all bare studied sites. Looking at the Figure 4, it can be observed that the $K_{r,text}-\theta_s$
 314 relationship shows two different shape curves: The S-shaped curve and the Γ -shaped curve.
 315 The shape curves depend on the P value which is different for each site due to the soil texture
 316 information. For the 33 bare soil sites, the P values ranged from 0.24 to 2.46 from sandy
 317 ($\theta_{1/2,1}$) to clayey ($\theta_{1/2,2}$) soils, respectively. For fine textured soils $K_{r,text}$ increased rapidly
 318 with the increase of θ_s while $K_{r,text}$ increased slower for coarse texture soils. The same
 319 behavior was observed with physically-based simulated Kr in Chanzy and Bruckler. (1993).
 320 For P value higher than 0.5 the $K_{r,text}$ increases rapidly with θ_s . In this case the derivative of
 321 Kr with respect to θ_s is equal to zero at $\theta_s = 0$ and when θ_s reaches the saturation (θ_{sat})
 322 $K_{r,text}$ equals 1. Contrarily, for the sites with a P value smaller than 0.5, the slope $\frac{\partial K_{r,text}}{\partial \theta}$ at
 323 $\theta_s = 0$ tends to infinity.

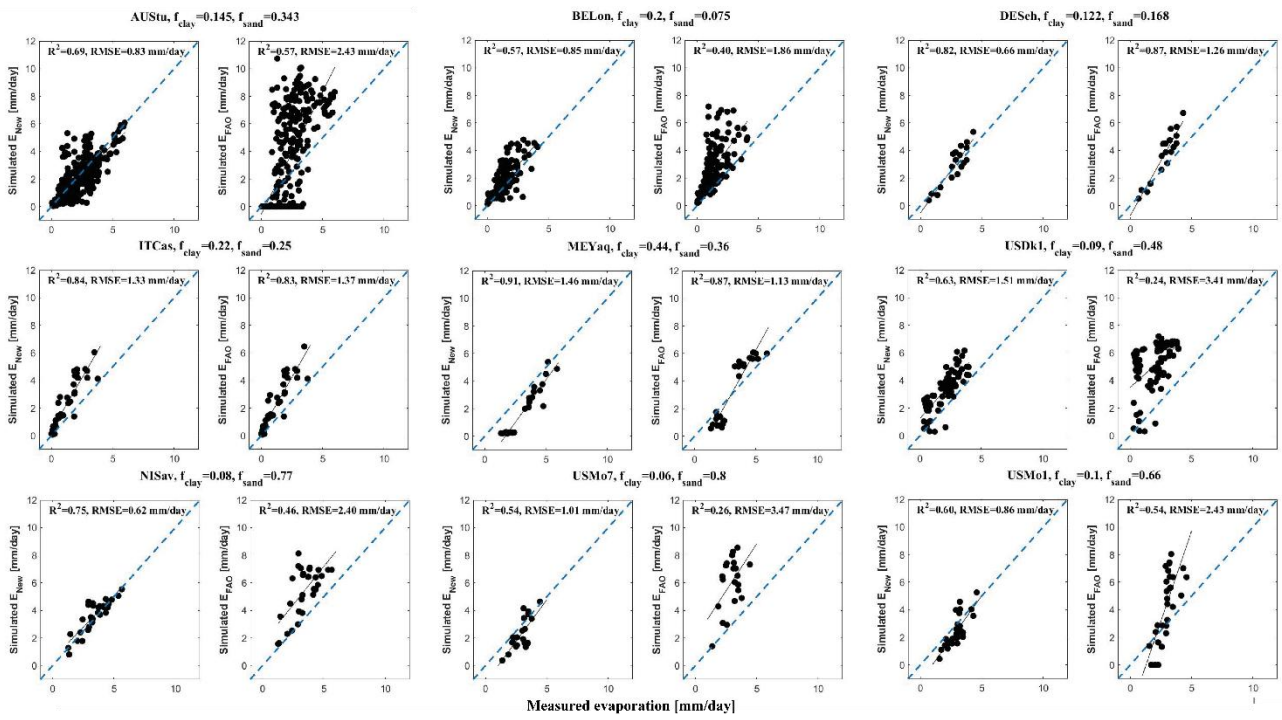


324

325 *Figure 4: Texture-based K_r simulated by the new model as function of in situ surface soil*
 326 *moisture for the different 33 used sites. The very clayey soil and very sandy soil in our data*
 327 *set correspond to P values equal to 2.46 and 0.24, respectively.*

328 **4.1. Evaporation estimates over bare soils using observed soil moisture** 329 **data**

330 In this sub-section we present the performance of the texture-based ($K_{r, \text{text}}$) by implementing a
 331 pedo-transfer function developed in Merlin et al. (2016) within the FAO formalism and the
 332 FAO ($K_{r, \text{FAO}}$) classical evaporation model compared to E measurements for some sites where
 333 the measurements are available. The developed model was tested over different soil texture
 334 sites (covering the range of clayey, silty, sandy soil types). Both methods were tested using *in*
 335 *situ* soil moisture measured at 0-5cm soil depth as forcing. Figure 5 shows the performance of
 336 the two methodologies; classical FAO (E_{FAO}) and texture-based formulation (E_{New}) compared
 337 to measurements for different ranges of clay, sand and silt fractions: silty loam (DESeh,
 338 AUStu, BELon and ITCas), sandy loam (NISav, USMo1), Clay (MEYaq) loam (USDk1) and
 339 loamy sand (USMo7). Key statistical information about model performance are reported in
 340 Figure 6 for all study sites, such as root mean square error (RMSE), determination coefficient
 341 (R^2) and mean bias error (MBE).

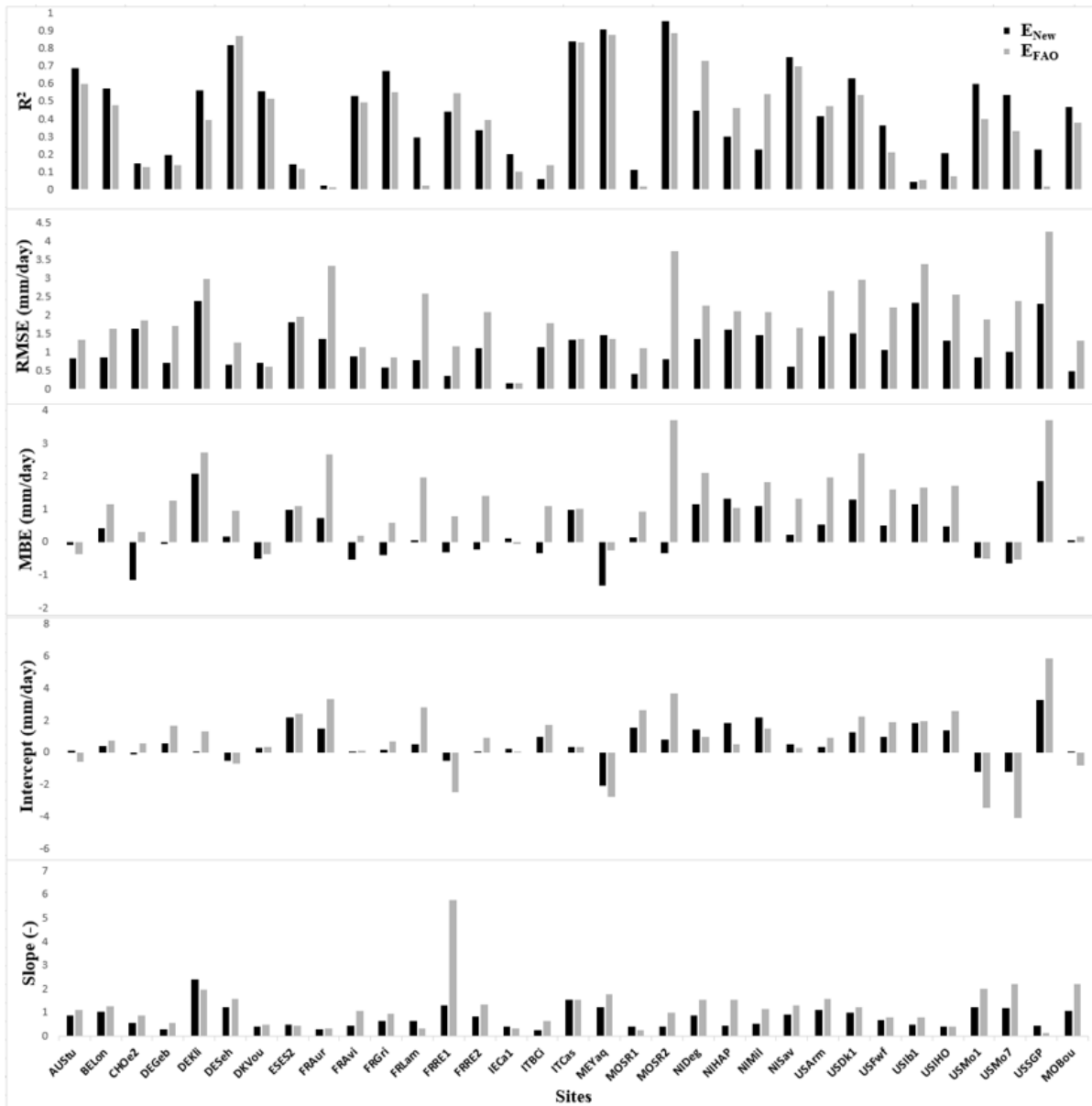


342

343

344

Figure 5: Evaporation estimates from new model (E_{New}) and FAO-2Kc (E_{FAO}) using soil moisture at 5-cm depth compared to measured evaporation.



345

346 *Figure 6: Bar graph of R^2 , RMSE, MBE, intercept and slope of the linear regression between*
 347 *simulated and observed E using the $K_{r_{text}}$ (black) and $K_{r_{FAO}}$ (grey) for each site.*

348 The scatter plot between observed and predicted E using the based-texture K_r (Figure 5)
 349 appears less dispersed around the 1:1 line compared to the classical $K_{r_{FAO}}$. Also, the bias is
 350 almost systematically reduced with the new texture-based formulation. A linear correlation is
 351 generally observed, which reveals that the new approach could be effective and successfully
 352 used to retrieve soil evaporation under different soil and climate conditions.

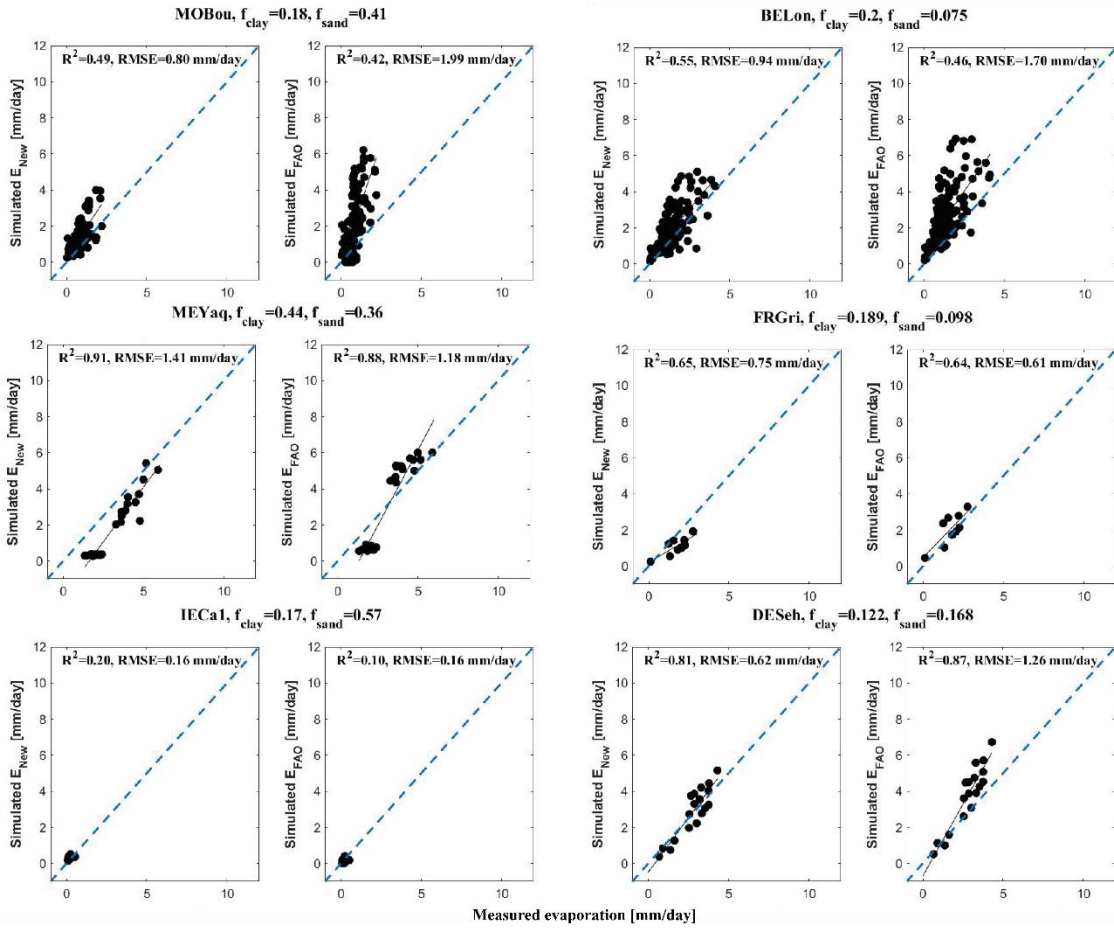
353 Although the statistical analyses provided relevant information about the effectiveness of the
 354 new developed model, statistical summary from Figure 6 revealed that the new K_r formalism
 355 has the capability to predict soil evaporation more accurately than the classical $K_{r_{FAO}}$. When

356 comparing the R^2 , RMSE, MBE, slope and intercept for each site, one can observe that the
357 performance of the new K_r based on soil texture information is better than the classical
358 representation of K_r . By using the new formalism, an improvement of R^2 from 0.57, 0.40 and
359 0.46 to 0.69, 0.57 and 0.75 with a decrease of RMSE from 2.43, 1.86 and 2.40 mm/day to
360 0.83, 0.85 and 0.62 mm/day is obtained for AUStu, BELon and NISav sites, respectively. The
361 texture-based $K_{r,\text{text}}$ appears to show its better performance for all soil types. For sandy loamy
362 soil we reached an R^2 of 0.75 (0.60) and a RMSE of 0.62 mm/day (0.86) for the NISav
363 (USMo1) site. For loamy sandy soil, R^2 reaches 0.54 with an RMSE equal to 1.01 mm/day for
364 USMo7 site, while for clayey soil as we reached an R^2 of 0.96 and RMSE of 0.80 for MOSR2
365 site.

366 In some study sites, even if the new approach still provides better results, a relatively poor
367 performance may occur for both approaches, (eg. USIb1, FRAur and CHOe2 sites). The
368 relatively poor results obtained at those sites are not due to the model itself but might be due
369 to the collected true measurements. As indicated in [Merlin et al. \(2016\)](#) most of the study sites
370 were not in a fully bare soil condition, as these sites were cropped and a selection of the
371 periods when soil is quasi bare was investigated, assuming no crop (no transpiration) over the
372 sites. This assumption could be a source of errors and could degrade the data quality. In
373 addition, soil depth could impact the results and could generate some uncertainties. To assess
374 the impact of the soil depth on the proposed approach, a sensitivity analysis is carried out by
375 using soil moisture at 0-10 cm depth. Overly, the new textural based K_r provides more
376 accurate results than the $K_{r,\text{FAO}}$. This is due to its physical basis, given that the $K_{r,\text{text}}$ is
377 implemented in a phenomenological model based on observational data, while the $K_{r,\text{FAO}}$ was
378 mainly built on ad hoc assumptions. [Lehmann et al. \(2018\)](#) showed the importance of soil
379 texture on the variation of surface evaporation as a function of soil moisture content.
380 Moreover, as cited in [Merlin et al. \(2016\)](#) and [Wetzel and Chang \(1988\)](#), the nonlinear
381 relationship between soil evaporation and soil moisture varied systematically with soil
382 properties. In addition, the critical soil moisture content where the evaporation rate drops
383 below potential rate, was related to soil texture through the field capacity ([Budyko, 1956](#);
384 [Manabe, 1969](#)). Through the new $K_{r,\text{text}}$, we succeeded in introducing the effect of soil texture
385 on E rate, which is not taken into account properly in other land surface models ([Phillips et](#)
386 [al., 2017](#)).

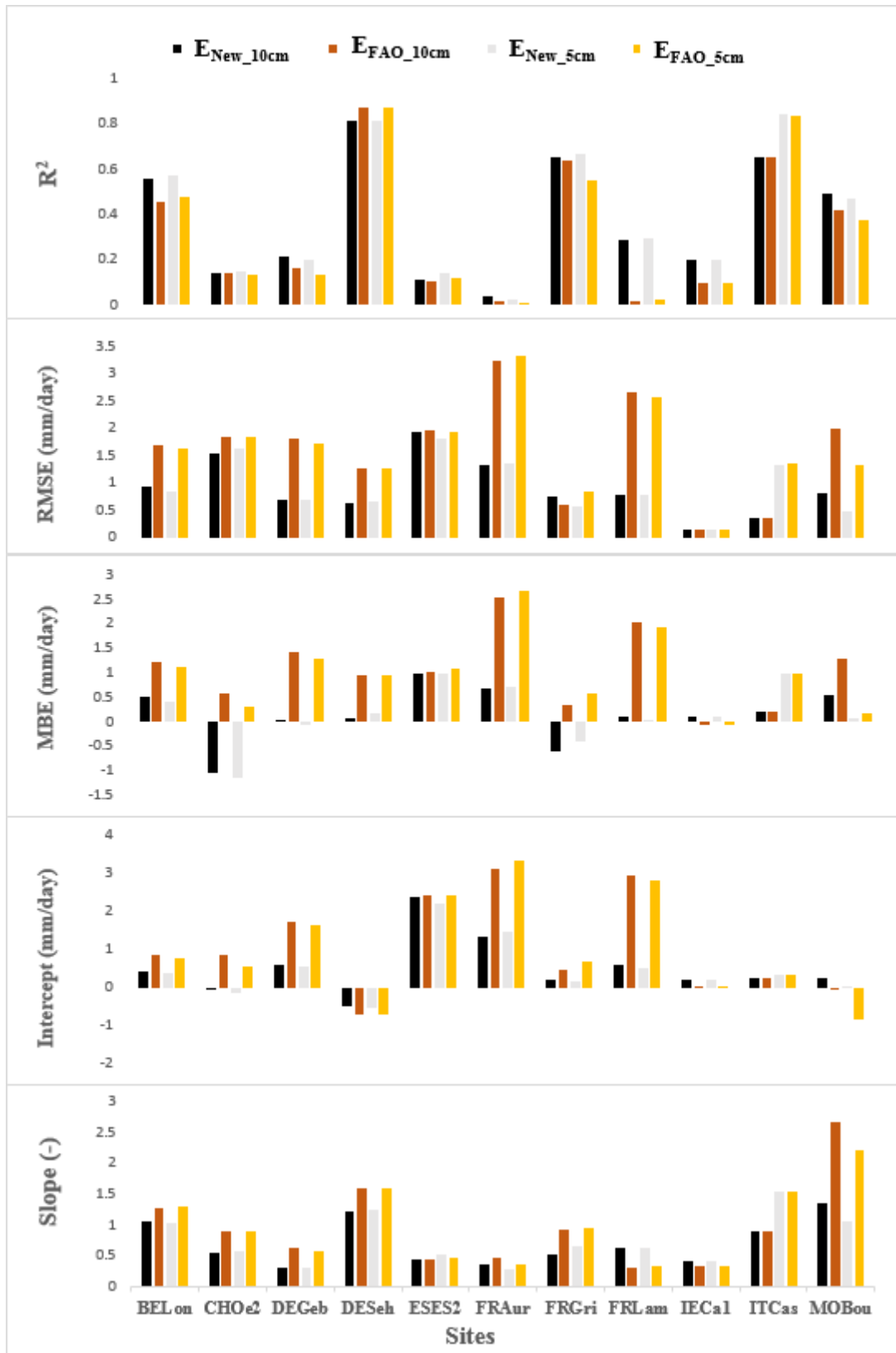
387 **4.2. Sensitivity of K_r formulations to the thickness of surface soil layer**

388 In this study the E estimates is assessed using soil moisture data at shallow depths near the
389 soil surface (0-5 cm and 0-10 cm depending on the site). As a prospect to integrate $K_{r, \text{text}}$ in
390 the FAO-2Kc (next sub-section), which uses a surface soil thickness (Z_e) of either 10 or 15
391 cm, we need to assess the applicability of the $K_{r, \text{text}}$ to the 0-15 cm soil layer. This is more
392 crucial as all soil evaporation formulations are sensitive to the thickness of the surface soil
393 layer (Merlin et al., 2011). Therefore, a sensitivity analysis has been made to quantify the
394 impact of active soil evaporation depth to E as well as the integration of the new $K_{r, \text{text}}$ into the
395 FAO-2Kc formulation. This was made for both approaches using 0-10 cm (in replacement of
396 the 0-5 cm) collected soil moisture. Note that, only the sites where soil moisture data at 10 cm
397 were available have been used for the sensitivity analysis. Figure 7 presents the simulated soil
398 E using texture-based $K_{r, \text{text}}$ and classical $K_{r, \text{FAO}}$ compared to *in-situ* measurements for the 0-
399 10 cm soil moisture depth. Due to the non-availability of soil moisture at 10 cm depth for all
400 sites, eleven sites were selected to test the new approach where soil moisture data at 10 cm
401 depth were available. Figure 7 shows the simulated evaporation using both classical $K_{r, \text{FAO}}$
402 and new model $K_{r, \text{text}}$ compared to *in situ* measurements for six sites with different soil
403 textures and climate conditions: clayey (MOBou, MEYaq), silty loam (BELon, FRGri,
404 DESeh) and sandy loam (IECa1). Figure 8 presents the performance of the approaches over
405 all the eleven study sites.



406

407 *Figure 7: Evaporation estimates from new model (E_{New}) and Kr_{FAO} (E_{FAO}) using soil moisture*
 408 *at 10 cm depth compared to measured evaporation.*



409

410 *Figure 8: Bar graph of the statistical parameters (R^2 , RMSE, MBE), the intercept and slope of the*
 411 *linear regression between simulated and observed E using the new texture-based (black '5cm', grey*
 412 *'10 cm') and K_{rFAO} (Brown '5cm', orange '10 cm') for each site. 5 cm and 10 cm are the soil depths.*

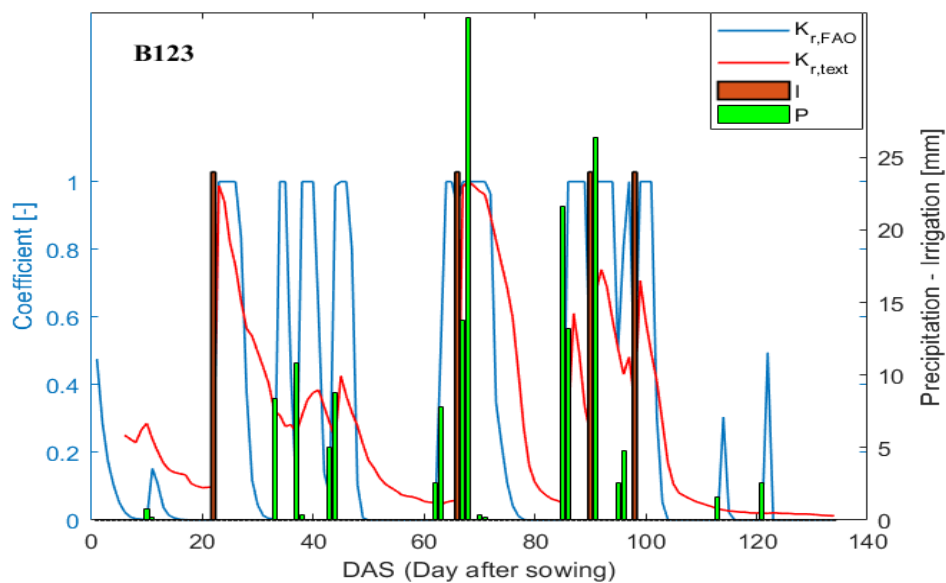
413 Looking at the results in Figures 7 and 8, generally the new textural-based model captures
414 well the variation of evaporation measurements. Mostly the new model provides a more
415 accurate prediction of E all over the 11 study sites. The new model shows its capabilities to
416 solve the common overestimation problem that occurs especially under arid and semi-arid
417 conditions (Michel et al., 2016) as shown at sites MOBou, BELon and DESeh. The new
418 model yielded lower RMSEs over almost all sites in comparison with classical K_{rFAO} , with a
419 value of 0.94 mm.day^{-1} and 1.70 mm.day^{-1} , respectively, at BELon site as an example.
420 The statistical results are presented in Figure 8, showing the performance of both approaches
421 (classic K_{rFAO} and new texture-based K_{rtext}) using soil moisture data at 0-5 cm and 0-10 cm
422 depth. In same sites, it appears from the statistical results that the performance of the new
423 approach slightly decreases while the classical K_{rFAO} slightly improves providing better
424 results by using soil moisture at 0-10 cm instead of 0-5 cm depths. However, the new
425 approach still outperformed the K_{rFAO} approach regardless of the sensing depth (0-5 or 0-10
426 cm) of the soil moisture measurements. The error between K_{rFAO} and *in-situ* evaporation
427 measurements is slightly reduced when using soil moisture at 0-10 cm instead of 0-5 cm
428 depths, from 0.85 to 0.60 mm.day^{-1} while by using new model the error is slightly increased
429 from 0.58 to 0.75 mm.day^{-1} over FRGri site. The improvement of the performance of K_{rFAO}
430 approach by using soil moisture at 0-10 cm instead of soil moisture at 0-5cm, is due to the fact
431 that the evaporation process can occur from deeper layers than the 0-5 cm layer. This is
432 especially occurred in arid and semi-arid areas in which the FAO-2Kc recommends the use of
433 a layer of 0-15 cm. Similarly, the new formulation of the evaporation reduction factor is
434 intrinsically dependent on the soil moisture measurements depth. It is reminded that the used
435 formulation has been developed and calibrated using a 0-5 cm soil layer. As stated by Merlin
436 et al. (2011), the P value is an increasing function of the soil depth for a given soil moisture
437 value. This could be responsible for the slight underestimation of new model when using the
438 0-10 cm layer. However, the K_{rFAO} formulation is generally based on moisture data from 0 to
439 15 cm (Allen, 2000). The sensitivity analysis shows that the new approach generally
440 outperformed the classical K_{rFAO} at either 5cm or 10 cm soil depths.

441 **4.3. Coupling the K_{rtext} model with the FAO crop water budget model:** 442 **application to wheat cropped fields**

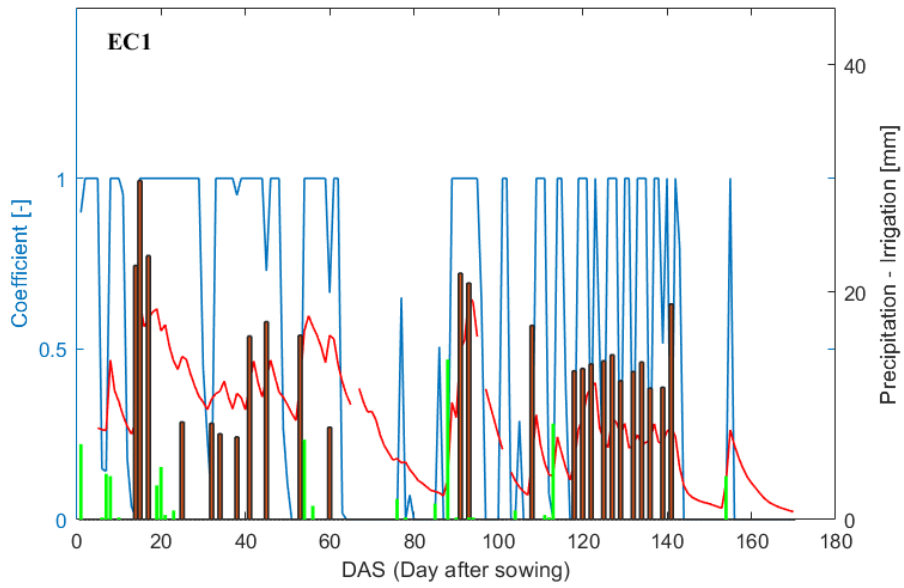
443 As mentioned above, the main objective is to improve the soil evaporation estimates through
444 using a formulation of Kr based on soil texture information and soil moisture estimates. The

445 point is that retrieving soil evaporation is more relevant over bare soils and sparse areas.
 446 However, over cropped area, retrieving surface evapotranspiration is more important. For this
 447 reason, as a source of validating of our approach, we tested the new textural-based Kr
 448 approach over the cropped fields defined before: B123 (2002-2003), EC1 and EC2 (2016-
 449 2017). Two cases were tested for each approach, where the soil evaporation component is
 450 forced by i) *in-situ* soil moisture θ_s , using the classical FAO-2Kc ($E_{FAO+\theta_s}$) or the new
 451 approach ($E_{New+\theta_s}$) and ii) simulated soil moisture from the water balance (θ_{FAO}), for
 452 classical FAO-2Kc and new approach termed in the plots as ($E_{FAO+\theta_{FAO}}$) and ($E_{New+\theta_{FAO}}$),
 453 respectively.

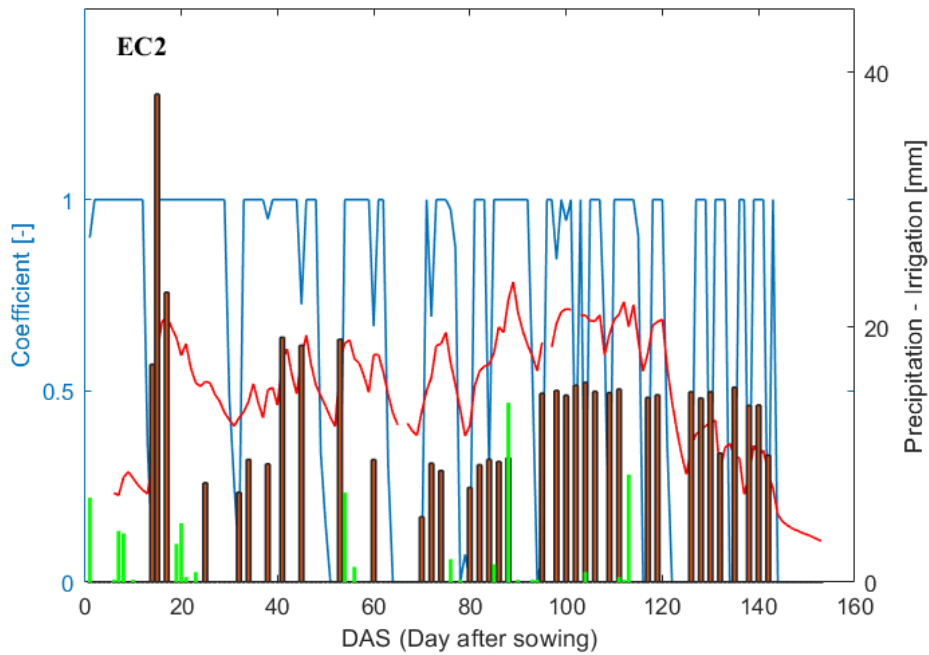
454 In order to observe the response of the evaporation coefficients to water supply, Figure 9
 455 shows the temporal variation of Kr for FAO-2Kc ($K_{r,FAO}$) and new textural-based Kr ($K_{r,text}$)
 456 approaches for the cropped fields.



457



458



459

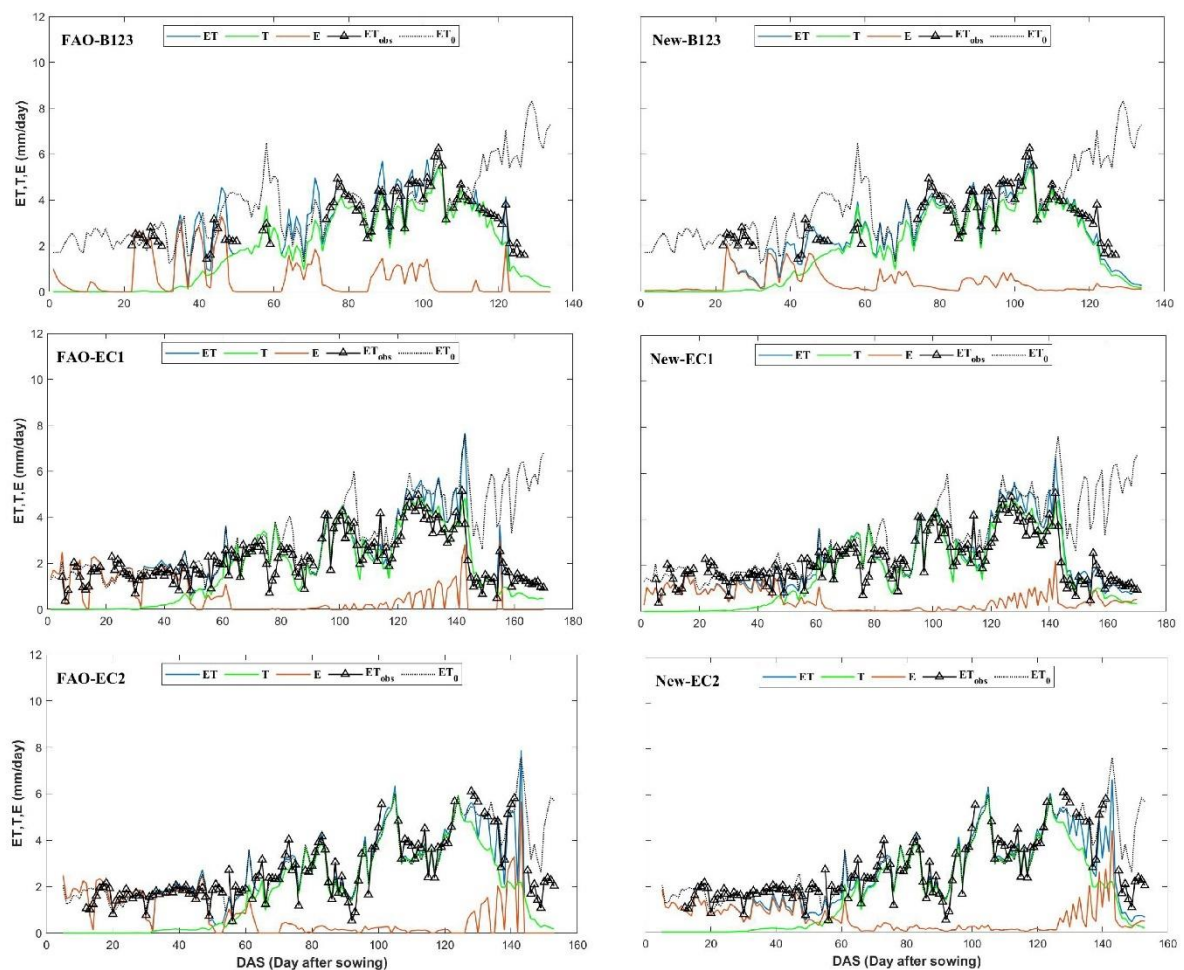
460 *Figure 9: Time variation of the K_r estimated from FAO-2Kc ($K_{r,FAO}$) and new textural based*
 461 *K_r ($K_{r,text}$) for the studied fields.*

462 From the Figure 9, it can be observed that at the initial stage of crop growth, the $K_{r,FAO}$ values
 463 are high and reach its maximal value (1). This is due to the small fraction of soil surface
 464 covered by wheat crop. In addition, following rain or irrigation both K_r increase, while the K_r
 465 is small and can reach zero in the drier periods when the soil resistance to evaporation
 466 increases.

467 Overall, $K_{r,\text{text}}$ detects soil stress periods and responds well to the water supplied by
 468 precipitation or/and irrigation. After an irrigation or precipitation event both Kr increase with
 469 different amplitudes. The new textural-based Kr appears to be more physical than the $K_{r,\text{FAO}}$.
 470 It consistently increases following the supplied water amounts and then gradually decreases.
 471 This is not the case for $K_{r,\text{FAO}}$, which increases and decreases rapidly. This is due to the
 472 response and the soil drying time which is well taken into account in the $K_{r,\text{text}}$ approach.
 473 Especially in stage 2 when soil moisture is the limiting factor, the $K_{r,\text{text}}$ decreases
 474 progressively for each soil type depending on the soil properties.

475 An increase of Kr comes with an increase of the evaporation rate after a water supply by
 476 irrigation or/and rain. Consequently, soil evaporation losses are considerable. Figure 10
 477 presents a daily evolution comparison of the measured ET (ET_{obs}) with simulated ET using
 478 standard FAO-2Kc ($E_{\text{FAO}}+\theta_{\text{FAO}}$) and new approach ($E_{\text{New}}+\theta_{\text{FAO}}$). Soil evaporation and wheat
 479 transpiration were also presented in the same figure for the three studied fields.

480

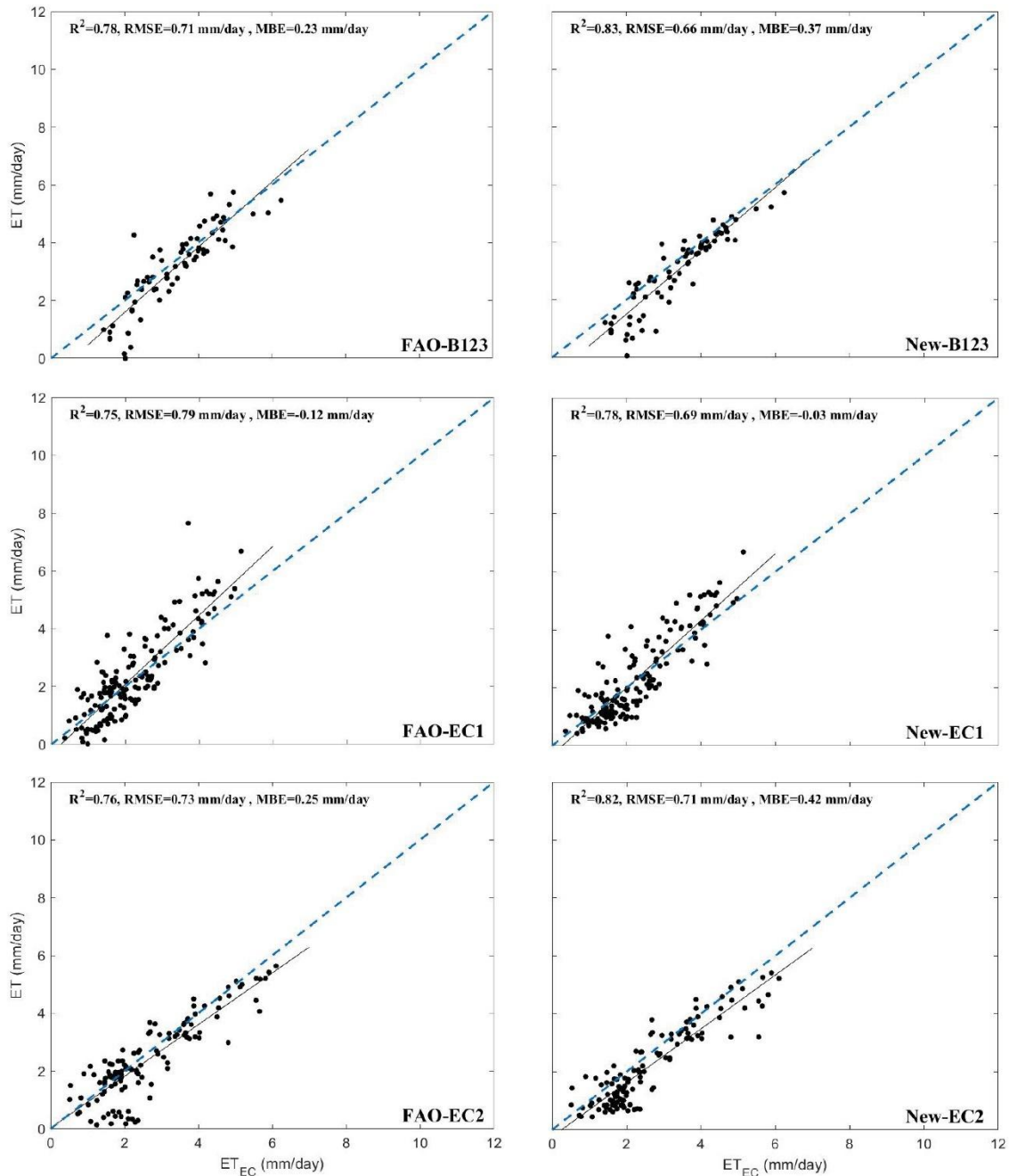


481

482 *Figure 10: Time series comparison of daily plant transpiration (T), soil evaporation (E), ET₀*
483 *as well as the ET observed by EC (ET_{obs}) and simulated by FAO-2Kc (left) and new model*
484 *(right) over the study fields.*

485 According to figure 10, we notice that the new approach follows correctly the measured ET.
486 As it is seen, the new formulation of E helps catch the variation of surface ET especially at the
487 beginning and the end of the season when ET is dominated by E and when transpiration is
488 relatively small. This behavior of the classical FAO-2Kc was also reported in [Rafi et al.](#)
489 [\(2019\)](#), where the classical FAO was found to underestimate E leading to an underestimation
490 of ET especially during the senescence period. While in [Olivera-Guerra et al. \(2018\)](#) an
491 overestimation issue was observed using thermal-derived E estimates. Using soil moisture and
492 texture information lead to a correction of E in the initial and late stage. To evaluate visually
493 and quantitatively the used approaches, the predicted ET were plotted against the observed ET
494 (ET_{EC}) and are presented in Figure 11 for the three wheat crop fields.

495



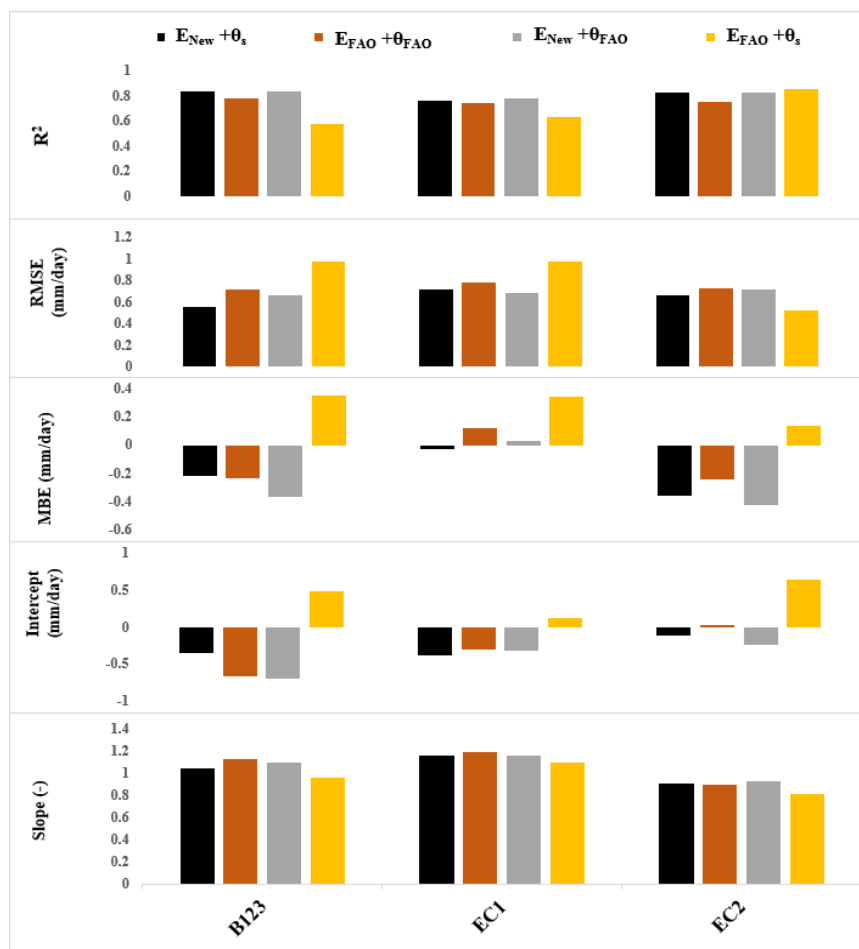
496

497 *Figure 11: Scatterplot of simulated ET-FAO using the FAO-2Kc (left plot) and the new model forced*
 498 *by simulated soil moisture (θ_{FAO}) (right plot) versus Eddy covariance ET (ET_{EC}) over the B123, EC1*
 499 *and EC2 study fields.*

500 From the statistical results presented in Figure 11, the new method provides the best results in
 501 term of accuracy and stability over the three wheat crop fields. The ET is estimated with an
 502 RMSE equal to 0.71 and 0.66 mm/day and an R^2 equal to 0.78 and 0.83 by using the classical
 503 FAO-2Kc and the proposed method for B123 field, respectively. An improvement is observed
 504 when using the new method. This is especially seen for small values of ET where the
 505 estimations are less scattered around the 1:1 line.

506 Statistics of the studied four cases are shown and reported in Figure 12. Using in situ soil
 507 moisture or simulated θ_s from water balance in the new model gives almost the same results.
 508 A slight difference is observed in the statistical results in terms of RMSE and R^2 . The
 509 $E_{New} + \theta_s$ shows the best results compared to the other methods with the lowest RMSE (0.55
 510 mm/day) and the highest R^2 of about 0.84 in the B123 field. The reason behind the good
 511 results when *in-situ* soil moisture was used is the fact that soil moisture is directly measured
 512 using TDR sensors while the simulated soil moisture is estimated using water balance
 513 equation where errors can accumulate from each water balance components. However, the
 514 classical approach shows good results compared to new approach in the EC2 field, although
 515 the difference between both approaches is smaller.

516 Overly, results showed that the new textural approach for E provided more accurate results in
 517 terms of ET regardless of the source (direct measurements and model simulations) of soil
 518 moisture estimates.



519
 520 *Figure 12: Bar graph of R^2 , RMSE, MBE, intercept and slope of the linear regression between*
 521 *simulated and observed ET using the 4 approaches.*

522 **5. Conclusion**

523 This work aims to improve the representation of the soil evaporation (E) component of the
524 total evapotranspiration (ET). In the classical FAO-2Kc, the evaporation reduction coefficient
525 Kr is estimated based on an ad-hoc relationship with soil texture. This standard formulation
526 provides some limitation to quantify the E process. [Rafi et al. \(2019\)](#) and [Olivera-Guerra et al.
527 \(2018\)](#) reported that the standard FAO-2Kc overestimates or underestimates E in the
528 beginning or/and the end of the agricultural season.

529 A new E formulation is developed by including the soil texture information into Kr. The idea
530 here is to adapt the Kr representation to the nonlinear relationship between soil moisture and
531 E in a range of soil texture types and surface conditions as in [Merlin et al. \(2016a, 2018\)](#). By
532 including the new formulation into the FAO-2Kc the typical drying process is modified. The
533 new evaporation formulation was tested over 33 bare soil sites distributed all over the world.
534 The sites are different in term of soil texture and meteorological conditions. Soil moisture
535 measurements at 0-5cm and 0-10 cm were used to further assess the impact of soil
536 measurement depths on the E rate. FAO-2Kc and the new texture-based approach were
537 evaluated by comparing them against in situ E measurements. From the obtained results, the
538 new approach provides the best results in term of accuracy and robustness. The new model
539 provided solid basis for describing the soil texture impact on the E reduction coefficient.
540 However, some uncertainties were observed, and this could be due to the water diffusion flux
541 which is not taken into account in the FAO-2Kc model and represents the soil as a simple
542 reservoir. Further, the new evaporation model was evaluated over a 3 monitored wheat
543 cropped fields, where evapotranspiration is retrieved. The simulated evapotranspiration was
544 compared to eddy covariance measurements installed in the 3 sites. A comparison of the 4
545 cases is investigated by using both standard FAO-2Kc and the new approach. Each model is
546 forced by soil moisture either measured in situ or simulated by the water balance model.
547 Results showed that the texture-based approach provides the best results with low errors over
548 the studied sites using field-scale measurements data.

549 To cope with some limitations of FAO-2Kc model, remote sensing data can be assimilated
550 ([Amazirh et al., 2021, 2018](#)). However, the use of remote sensing data in the FAO-2Kc would
551 require a match between the soil layers represented by the model and the sensing depth of
552 spaceborne observations. The point is that the sensed thickness of remote sensing data rarely
553 exceeds 0-5 cm. In this vein, coupling the FAO-2Kc with remote sensing data will be an asset
554 for minimizing modeling errors, and for better constraining the ‘often unavailable over most

555 irrigated area' irrigation input data. To do this, changing the depth of the top-soil layer
556 represented by the FAO-2Kc model to fit with the near-surface soil moisture derived from
557 remote sensing is needed.

558

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565 was provided by the Joint International Laboratory TREMA (<http://trema.ucam.ac.ma>), the
566 European Fluxes Database Cluster (<http://www.europe-fluxdata.eu>), the AmeriFlux sites,
567 OzFlux site, long term observatories (AMMA, HOBE and SudMed), and the short term
568 intensive field campaigns (EFEDA, ReSeDa, Yaqui'08, HAPEX-Sahel, IHOP, Monsoon'90
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571 evaporation database.

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