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## **Simulation of evapotranspiration and yield of maize**

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1 **Simulation of Evapotranspiration and Yield of Maize:**  
2 **An Inter-comparison among 41 Maize Models**

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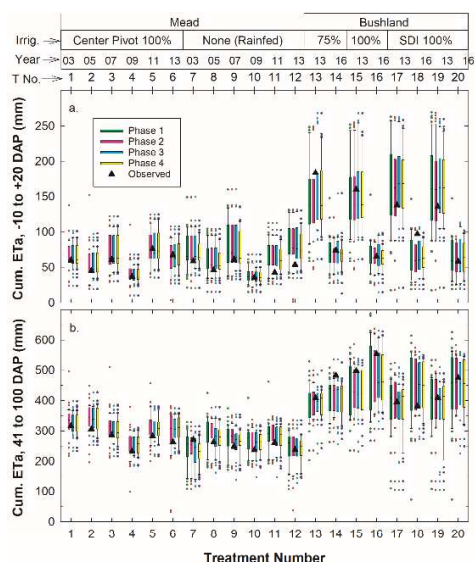
115 **Abstract**

116 Accurate simulation of crop water use (evapotranspiration, ET) can help crop growth models to  
117 assess the likely effects of climate change on future crop productivity, as well as being an aid for  
118 irrigation scheduling for today's growers. To determine how well maize (*Zea mays* L.) growth  
119 models can simulate ET, an initial inter-comparison study was conducted in 2019 under the  
120 umbrella of AgMIP (Agricultural Model Inter-Comparison and Improvement Project). Herein,  
121 we present results of a second inter-comparison study of 41 maize models that was conducted  
122 using more comprehensive datasets from two additional sites - Mead, Nebraska, USA and

123 Bushland, Texas, USA. There were 20 treatment-years with varying irrigation levels over  
 124 multiple seasons at both sites. ET was measured using eddy covariance at Mead and using large  
 125 weighing lysimeters at Bushland. A wide range in ET rates was simulated among the models, yet  
 126 several generally were able to simulate ET rates adequately. The ensemble median values were  
 127 generally close to the observations, but a few of the models sometimes performed better than the  
 128 median. Many of the models that did well at simulating ET for the Mead site did poorly for drier,  
 129 windy days at the Bushland site, suggesting they need to improve how they handle humidity and  
 130 wind. Additional variability came from the approaches used to simulate soil water evaporation.  
 131 Fortunately, several models were identified that did well at simulating soil water evaporation,  
 132 canopy transpiration, biomass accumulation, and grain yield. These models were older and have  
 133 been widely used, which suggests that a larger number of users have tested these models over a  
 134 wider range of conditions leading to their improvement. These revelations of the better  
 135 approaches are leading to model improvements and more accurate simulations of ET.

136

137 **Graphical abstract**



138

139 **Highlights**

- 140 • Maize growth models differ widely in their simulations of daily evapotranspiration
- 141 • Most models fail to sufficiently reduce transpiration after crop maturation
- 142 • Most models fail to adequately reproduce effects of low humidity and high windspeed
- 143 • The median of models was often but not always the best performing
- 144 • Model inter-comparisons suggest avenues to improve simulation of maize ET

145

146 **Keywords:** Maize; simulation; evapotranspiration; water use; crop models; yield

147 **1 Introduction**

148 Crop growth models are a useful management aid for today’s farmers, as well as being a tool to

149 forecast the likely effects of climate change on future agricultural productivity and irrigation

150 water requirements. For both tasks they need to be accurate. Therefore, in a major effort to

151 improve their accuracy and reliability, modeling groups within the Agricultural Model Inter-

152 comparison and Improvement Project (AgMIP; <https://agmip.org/>) have been inter-comparing

153 multiple models against each other and against field datasets with varying CO<sub>2</sub>, temperature,

154 nitrogen fertilizer, and water supply [wheat (*Triticum aestivum* L.; Asseng et al., 2013, 2015;

155 Cammarano et al., 2016; Liu et al., 2016; Maiorano et al., 2017; Wang et al., 2017), maize (*Zea*

156 *mays* L.; Bassu et al., 2014; Durand et al., 2018; Kimball et al., 2019), rice (*Oryza sativa* L.; Li

157 <sup>1</sup> Abbreviations: ASCE – American Society of Civil Engineers, DAP – days after planting, E –

158 soil water evaporation, Ep – potential soil water evaporation, Es – simulated soil water

159 evaporation, ET – evapotranspiration, ETo – “short” reference evapotranspiration based on 12-

160 cm-tall grass, ETp – potential evapotranspiration, ETr – “tall” reference evapotranspiration based

161 on 50-cm-tall alfalfa, ETs – simulated evapotranspiration, LAI, leaf area index, nRMSE –

162 normalized root mean square error, MESA – mid-elevation sprinkler application, P-T – Priestley-

163 Taylor, SDI – subsurface drip irrigation, T – transpiration, Tp – potential canopy transpiration,

164 Ts – simulated canopy transpiration

165



166 et al., 2015; Hasegawa et al., 2017), and potato (*Solanum tuberosum* L.; Fleisher et al., 2017)].  
167 As discussed by Kimball et al. (2019), only a few comparisons among methods or models to  
168 simulate ET have been done previously. Sau et al. (2004) evaluated several ET options with the  
169 CROPGRO Faba bean (*Vicia faba* L.) model, by careful comparison to soil water balance, and  
170 found that the FAO-56 option (Allen et al., 1998) had a root mean square error (RMSE) that was  
171 20% smaller than the Priestley-Taylor option (Priestley and Taylor, 1972) and 48% smaller than  
172 the FAO-24 option (Doorenbos and Pruitt, 1985). In an inter-comparison of water use among 16  
173 wheat models at four sites around the world, Cammarano et al. (2016) found the coefficient of  
174 variation was only 22.5% among models and sites. In contrast, in an inter-comparison among 23  
175 maize models, Bassu et al. (2014) found a very large range of simulated values of ET among the  
176 models, including -10 to +30% variations in the ET response to doubled CO<sub>2</sub> concentration (720  
177 μmol/mol). However, there were no observations of ET or water use in the dataset chosen for  
178 that study, so there was no standard for comparison. Therefore, Kimball et al. (2019) conducted  
179 their study using eight seasons of data from Ames, Iowa, USA for which eddy covariance  
180 measurements of ET were available. Like Bassu et al. (2014), they also found simulated ET  
181 values varied by a factor of two among the maize models. Surprisingly, among the models with  
182 closest agreement to observations, some were quite simple (e.g., no simulation of biomass) and  
183 some were quite complex (e.g., full energy balance), so it was difficult to determine which  
184 approaches were generally best and should be adopted by the poorer performing models.  
185 Nevertheless, there were several cases in which different ET methods were tested within the  
186 same family of crop models, and comparisons among these methods clearly revealed some  
187 approaches that were better than others.

188

189 However, there were some issues with the Ames dataset (Kimball et al., 2019). For example, in  
190 2012, an infamous year for drought in the Midwest, observed ET and crop yield were higher than  
191 in other years. Further analysis led to the strong suspicion that there was a water table present to  
192 provide additional water besides the sparse rainfall, yet deep soil water measurements were  
193 lacking to confirm the suspicion. Therefore, it was decided to repeat the study of Kimball et al.  
194 (2019) with more robust datasets.

195

196 Two such datasets were identified, one from the University of Nebraska at Mead, Nebraska,  
197 USA (41.165°N, 96.470°W, 362 m), which is close to the 100<sup>th</sup> meridian typically used to divide  
198 the humid East from the arid West, thus placing it within the U.S. “corn belt.” There were six  
199 seasons of maize from irrigated and rainfed fields (12 treatment-years) with ET determined using  
200 eddy covariance. The second was collected by the USDA, Agricultural Research Service,  
201 Conservation and Production Research Laboratory (CPRL), Bushland, Texas, USA (35.183°N,  
202 102.100°W, 1170 m), which is a more arid region where maize is mostly grown with irrigation,  
203 and where winds are commonly higher. They measured ET using large weighing lysimeters.  
204 They grew maize for two seasons with MESA (mid-elevation sprinkler application) at 100% and  
205 75% replacement of soil water and in near-duplicate SDI (sub-surface drip irrigation) fields at  
206 100% (8 treatment-years). A total of 41 models participated in this second round of maize ET  
207 simulation inter-comparisons (Tables 1, S1), and again the primary objective was to identify the  
208 approaches that were most accurate for simulating ET, i.e., had the lowest RMSE compared to  
209 the observations. Besides ET, other objectives were to test the models’ abilities to simulate LAI,  
210 biomass, grain yield, soil moisture, and soil temperature. By “approaches” we mean the methods

211 used by the models to simulate ET or other processes, i.e., FAO-56 (Allen et al. 1998) versus  
212 Priestley-Taylor (1972), etc.

213

214

## 215 **2 Materials and Methods**

### 216 *2.1 Observed data*

#### 217 *2.1.1 University of Nebraska, Mead, Nebraska, USA*

218 One set of field data came from the University of Nebraska Agricultural Research and  
219 Development Center near Mead, Nebraska, USA (<http://csp.unl.edu/public/>). The soils were deep  
220 silty clay loams of Yutan (fine-silty, mixed, superactive, mesic Mollic Hapludalfs), Tomek (fine,  
221 smectitic, mesic Pachic Argialbolls), Filbert (fine, smectitic, mesic Vertic Argialbolls), and  
222 Filmore (fine, smectitic, mesic Vertic Argialbolls). The eddy covariance technique was used to  
223 determine ET of maize and soybean (*Glycine max*) in alternate years, as well as fluxes of  
224 sensible heat and CO<sub>2</sub>. Additional details can be found in Suyker and Verma (2008, 2009) and  
225 Suyker et al. (2004, 2005). Briefly, fluxes of latent heat, sensible heat, and momentum were  
226 determined using data from the following sensors at each site: an omnidirectional 3D sonic  
227 anemometer (Model R3: Gill Instruments Ltd., Lymington, UK) and an open-path infrared  
228 CO<sub>2</sub>/H<sub>2</sub>O gas analyzing system (Model LI7500: Li-Cor Inc., Lincoln, NE).

229

230 The instruments were deployed near the centers of the fields, and the fetch was about 400 m in  
231 all directions. The eddy covariance sensors were mounted 5.5 m above the ground. Fluxes were  
232 corrected for inadequate sensor frequency, and they were also adjusted for the variation in air  
233 density due to the transfer of water vapor and sensible heat. Air temperature and relative

234 humidity (Humitter50Y, Vaisala, Helsinki, FIN), soil heat flux at 0.06m (Radiation and Energy  
235 Balance Systems, Inc., Seattle, WA), and net radiation at 5.5m (CNR1, Kipp and Zonen Ltd.,  
236 Delft, NLD) were also measured. Missing data due to sensor malfunction, power outages,  
237 unfavorable weather, etc. (approximately 15–20% per year), were estimated using an approach  
238 that combined measurement, interpolation, and empirical data synthesis. When hourly values  
239 were missing (day or night), the latent heat values were estimated as a function of available  
240 energy. Linear regressions between latent heat and available energy were determined (separately  
241 for dry and wet conditions) for sliding 3-day intervals, and these estimates were used to fill in  
242 missing flux values.

243

244 To check closure of the energy balance, the sum of latent and sensible heat fluxes ( $\lambda E + H$ )  
245 measured by eddy covariance were plotted against the sum of  $R_n$  (net radiation) + four storage  
246 terms, determined by other methods (e.g., Suyker and Verma, 2008). Linear regressions were  
247 calculated between the hourly values of  $H + \lambda E$  and  $R_n + G$  at the study sites (excluding winter  
248 months and periods with rain and irrigation). Here  $G = G_s$  (soil heat storage) +  $G_c$  (canopy heat  
249 storage) +  $G_m$  (heat stored in the mulch) +  $G_p$  (energy used in photosynthesis). The regression  
250 slopes averaged  $0.89 \pm 0.08$ , implying a fairly good closure of the energy balance.

251

252 We used values of daily ET flux, called observed-ET for 2003, 2005, 2007, 2009, 2011, and  
253 2013 from the US-Ne2 (41.165° N, 96.470° W, 362 m; [http://ameriflux.lbl.gov/sites/siteinfo/US-](http://ameriflux.lbl.gov/sites/siteinfo/US-Ne2)  
254 [Ne2](http://ameriflux.lbl.gov/sites/siteinfo/US-Ne2)) irrigated maize-soybean rotation field and from the US-Ne3 (41.180° N, 96.440° W, 363  
255 m; <http://ameriflux.lbl.gov/sites/siteinfo/US-Ne3>) rainfed maize-soybean rotation field.

256 Conservation tillage practices were used, so plant residues were not ploughed into the soil, and

257 the soil surface was generally partially covered with prior soybean crop residue. Both sites are  
258 part of the Ameriflux (<https://ameriflux.lbl.gov/sites>) U.S. surface gas flux observation system,  
259 and the two sites are within 1.6 km of each other. The cultivars were Pn33B51, Pn33G66,  
260 Pn33H26, Pn33T57, DK\_61-72, and DK\_62-98 used in 2003, 2005, 2007, 2009, 2011, and 2013,  
261 respectively. The irrigated crops were planted on 14 May, 2 May, 1 May, 21 April, 17 May, and  
262 30 May, and the rainfed crops on 13 May, 26 April, 2 May, 22 April, 2 May, and 13 May in  
263 2003, 2005, 2007, 2009, 2011, and 2013, respectively. Destructive measurements of green leaf  
264 area index (LAI) and biomass were made approximately bi-monthly during the growing season.

265

266 *2.1.2 USDA, Agricultural Research Service, Conservation and Production Research Laboratory,*  
267 *Bushland, Texas, USA*

268 Maize was grown in 2013 and 2016 at the USDA-ARS Conservation and Production Research  
269 Laboratory (<https://www.ars.usda.gov/plains-area/bushland-tx/cprl/>), Bushland, Texas (35.18° N,  
270 102.10° W, 1170 m above MSL) on a gently sloping (<0.3%) Pullman soil (fine, mixed,  
271 superactive, thermic Torrertic Paleustoll). Additional details and data are provided by Evett et al.  
272 (2019, 2020, 2022). Four 4.4 ha fields, approximately square in shape and adjacent to each other,  
273 each contained a large (3 m × 3 m in surface area, 2.3 m deep) precision weighing lysimeter in  
274 the center. The lysimeters contained undisturbed cores of the Pullman soil obtained on site, and  
275 they had an accuracy of 0.04 mm water depth equivalent or better (Evett et al., 2012; Marek et  
276 al., 1988). The fields and their associated lysimeters were designated NE, SE, NW, and SW  
277 according to the inter-cardinal directions. The NE and SE lysimeters and fields were irrigated by  
278 subsurface drip irrigation (SDI), and the NW and SW lysimeters and fields were irrigated by  
279 mid-elevation sprinkler application (MESA) using a ten-span linear-move system described by

280 Evett et al. (2019). Adaptation of SDI for the NE and SE weighing lysimeters was described by  
281 Evett et al. (2018a). A 109-day drought-tolerant variety (Pioneer 1151AM AquaMax,  $\leq 80\%$  Bt)  
282 was planted on 16-17 May 2013 under MESA irrigation, on 22-23 May 2013 in the SDI fields  
283 and on 10-11 May 2016 in all fields. These are typical dates for maize planting in the region.  
284 Crops were managed and fertilized for high grain yield, as detailed by Evett et al. (2019). In each  
285 field, destructive subsampling for leaf area index and biomass occurred in replicate plots  
286 periodically during the season, and plant height and row width were measured at the same times.  
287 Maize harvests were on 15 October 2013 and on 13 and 17 October 2016.

288

289 Soil water content was sensed at center depths of 0.10 to 2.30 m in 0.20 m increments in each of  
290 eight access tubes in the field around each lysimeter and in two access tubes in each lysimeter (to  
291 1.90 m depth) on a weekly basis, unless prevented by wet field conditions, using a field-  
292 calibrated neutron probe and depth-control stand (Evett et al., 2008). Once the crop was  
293 established, irrigations were scheduled weekly to replenish the soil water in the top 1.5 m of the  
294 profile to field capacity (i.e., replenishing 100% of crop ET), except for one MESA field where  
295 irrigations were 75% of full crop ET after crop establishment. As explained by Evett et al.  
296 (2019), the MESA 75% deficit irrigation treatment was established to complete a previous  
297 longer-term deficit irrigation study. In some cases, two or even three irrigations were required in  
298 a week to replenish the water used by the crop. Irrigations by sprinkler and by SDI typically did  
299 not occur on the same day. Neutron probe readings were delayed until the soil surface was dry  
300 enough to walk on. The soil profile in early 2013 was quite dry, and SDI preplant irrigation and  
301 SDI irrigation immediately after planting were required to plant and germinate the crop. This  
302 resulted in a full soil profile in the SDI fields by the time neutron probe sensing began, while

303 crop germination with MESA irrigation was accomplished with less frequent irrigations that did  
304 not penetrate to the 1.5 m depth. Irrigations in the 100% SDI and MESA fields maintained the  
305 soil water depletion to less than the management-allowed depletion level throughout the season.  
306 In 2016, the soil profile was much wetter following a wet winter, and no preplant irrigation and  
307 less irrigation immediately after planting were needed. Again, irrigations in the 100% SDI and  
308 MESA fields kept soil water depletion to less than the management-allowed depletion level.

309

310 Evapotranspiration (ET) was determined on 5 min, 15 min, and daily bases using data analyses  
311 and quality control procedures described by Marek et al. (2014) and Evett et al. (2019). Fifteen-  
312 minute-average weather data were output from the research weather station of the USDA-ARS  
313 Soil and Water Management Research Unit at Bushland, Texas located immediately east of the  
314 lysimeter fields. The weather station instrumentation and data quality assurance and control  
315 procedures were applied as described by Evett et al. (2018b).

316

## 317 *2.2 Modeling methodology*

318 *2.2.1 Model list.* The simulations were conducted by 20 modeling groups from around the world  
319 with 41 models completing the inter-comparison (Table 1). Details about each model are  
320 presented in supplementary Table S1. However, as can be seen from the names (Tables 1, S1), in  
321 some cases there were several “flavors” of different simulation methods tested within the same  
322 model family that were chosen by the user at run time. The biggest example is that of the  
323 DSSAT family (Hoogenboom et al., 2019a,b; Jones et al., 2003) of the Cropping System Model  
324 (CSM) within which both the CSM-CERES-Maize and CSM-IXIM-Maize (hereafter simply  
325 called CERES and IXIM) modules were run. Both calculate a value called potential  
326 evapotranspiration, ET<sub>p</sub>, which was done using four methods: (1) FAO-56 (Allen et al., 1998),

327 (2) Priestley-Taylor (1972), (3) the ASCE Standardized Reference Evapotranspiration Equation  
328 (Allen et al., 2005) for 12-cm grass (short crop), and (4) the ASCE Equation for 50-cm alfalfa  
329 (tall crop; *Medicago sativa* L.) with FAO-56 dual crop coefficients for maize (Table S1). Within  
330 these eight combinations, two E methods for calculating soil water evaporation were tested:  
331 “Ritchie” (Ritchie, 1972) and “Suleiman” (Suleiman and Ritchie, 2003, 2004). In addition,  
332 within the CERES-FAO-56 and CERES-Priestley-Taylor combinations, E was also computed  
333 using Hydrus (Šimůnek et al., 1998, 2008; Shelia et al., 2018), in which soil water moves based  
334 on potential gradients. Thus, there were a total of 18 (2 models x 4 ETp methods x 2 soil E  
335 methods + 2 Hydrus) DSSAT flavors. Within the DSSAT flavors, model calibrations though  
336 Phase 4 were aimed at the best statistics [lowest RMSE, and highest D-statistic (Willmont,  
337 1982)] for growth, grain yield, ET, and soil water variables, averaged over four ET options (two  
338 ET by two E methods) in order to minimize bias. The ASCE and Hydrus ET options were not  
339 included in this process because the methods were not part of the DSSAT V4.7 release, so they  
340 were at a slight disadvantage because they were not independently calibrated. Nevertheless, the  
341 resulting cultivar coefficients were consistently used among all the DSSAT simulations.

342  
343 In addition, Expert-N had GECROS and SPASS flavors, STICS had KETP and ETP\_SW  
344 flavors, and MAZSIM had daily and hourly flavors.

345

346



347 Table 1. List of models and their acronyms. (For details about the evapotranspiration aspects of  
348 each, see Supplementary Table S1: List of Models Plus Their Simulation Characteristics and  
349 Comparisons of Soil Moisture Simulations)  
350

<b>Acronym</b>	<b>Model Name</b>	<b>Reference</b>
AHC	Agro-Hydrological & chemical & Crop sys. simulator	Williams et al., 1989
AMSW	APSIM-SOILWAT	Keating et al., 2003
AQCP	AquaCrop	Allen et al., 1998
AQY	Aqyield	Constantin et al., 2015
ARMO	ARMOSA	Perego et al., 2013
BIOM	Biome-BGCMuSo 6.0.2	Hidy et al., 2016
CS	CropSyst4	Stöckle et al., 2003
DACT	DayCent-CABBI	Moore et al., 2020
DCAR	DSSAT CSM-CERES-Maize ASCE-Alfalfa Ritchie	DeJonge & Thorp, 2017
DCAS	DSSAT CSM-CERES-Maize ASCE-Alfalfa Suleiman	DeJonge & Thorp, 2017
DCFH	DSSAT CSM-CERES-Maize FAO-56 Hydrus	Shelia et al., 2018
DCFR	DSSAT CSM-CERES Maize FAO-56 Ritchie	Sau et al., 2004
DCFS	DSSAT CSM-CERES-Maize FAO-56 Suleiman	Sau et al., 2004
DCGR	DSSAT CSM-CERES-Maize ASCE-Grass Ritchie	DeJonge & Thorp, 2017
DCGS	DSSAT CSM-CERES-Maize ASCE-Grass Suleiman	DeJonge & Thorp, 2017
DCPH	DSSAT CSM-CERES-Maize Priestley-Taylor Hydrus	Shelia et al., 2018
DCPR	DSSAT CSM-CERES-Maize Priestley-Taylor Ritchie	Sau et al., 2004
DCPS	DSSAT CSM-CERES-Maize Priestley-Taylor Suleiman	Sau et al., 2004
DIAR	DSSAT CSM-IXIM-Maize ASCE-Alfalfa Ritchie	DeJonge & Thorp, 2017
DIAS	DSSAT CSM-IXIM-Maize ASCE-Alfalfa Suleiman	DeJonge & Thorp, 2017
DIFR	DSSAT CSM-IXIM-Maize FAO-56 Ritchie	Sau et al., 2004
DIFS	DSSAT CSM-IXIM-Maize FAO-56 Suleiman	Sau et al., 2004
DIGR	DSSAT CSM-IXIM-Maize ASCE-Grass Ritchie	DeJonge & Thorp, 2017

<b>Acronym</b>	<b>Model Name</b>	<b>Reference</b>
DIGS	DSSAT CSM-IXIM-Maize ASCE-Grass Suleiman	DeJonge & Thorp, 2017
DIPR	DSSAT CSM-IXIM-Maize Priestley-Taylor Ritchie	Sau et al., 2004
DIPS	DSSAT CSM-IXIM-Maize Priestley-Taylor Suleiman	Sau et al., 2004
ECOS	ecosys	Grant & Flanagan, 2007
JUL	JULES	Best et al., 2011
L5SH	L5-SLIM-H	Wolf, 2012
MZD	MAIZSIM Daily	Yang et al., 2009
MZH	MAIZSIM Hourly	Yang et al., 2009
SLUS	SALUS	Basso & Ritchie, 2015
SLFT	SIMPLACE LINTUL5 FAO56 SLIM3 CanopyT	Wolf, 2012
SMET	SIMETAW#	Mancosu et al 2016
SSMi	SSM-iCROP	Soltani & Sinclair, 2012
STCK	STICS_KETP	Brisson et al., 2003
STSW	STICS_ETP_SW	Brisson et al., 2003
SWB	SWB	Annandale et al., 2000
TMOD	Test Model	
XNGM	Expert-N - GECROS	Priesack et al., 2006
XNSM	Expert-N - SPASS	Priesack et al., 2006

351

352 2.2.2 *Simulation protocol*. The study was conducted in four phases:

- 353 1. “Blind phase.” The modelers were sent key input data about soils, weather, and  
354 management (planting dates, irrigations, fertilizer applications, etc.) information. They  
355 also received anthesis and maturity dates, but no other information about plant growth,  
356 grain yield, or water use.
- 357 2. “Potential or non-stressed growth phase”. The modelers were sent time-series leaf area  
358 index (LAI) and biomass observations, as well as final grain yields for all the non-water-  
359 stress treatments (only irrigated for Mead; only 100% irrigation for Bushland)
- 360 3. “Non-stress ET phase”. The modelers were sent all ET, soil water, and soil temperature  
361 for the non-water-stress treatments (only irrigated for Mead; only 100% irrigation for  
362 Bushland)
- 363 4. “All phase”. In this final phase, the modelers were provided with all LAI, biomass, grain  
364 yield, ET, soil moisture, soil temperature etc. data for all treatment-years.

365

366 The modelers were told to start their simulations on day-of-year 91, so there would be time for  
367 equilibration of soil moisture and soil temperature. They were also provided “initial” soil water  
368 content profiles, but the number of days before planting at which soil moisture was determined  
369 varied widely from season to season.

370

371 2.2.3 *Methods for evaluating model performance*

372 Correlation coefficients ( $r$ ), D statistics (Willmott, 1982), root mean squared errors between  
373 observed and simulated values (RMSE), normalized root mean squared errors (nRMSE), average  
374 differences, as well as mean squared deviations (MSD), standard bias (SB), non-unity of slopes

375 (NU), and lack of correlations (LC) following Gauch et al. (2003), are all presented as  
376 Supplementary Statistical Data for Phase 4. Also included are slopes and intercepts of  
377 regressions of observed on simulated data, along with corresponding graphs for each model and  
378 analyzed parameter.

379 Herein, we chose to present the nRMSE results calculated using:

$$380 \text{ nRMSE} = \{[n^{-1} \sum (P_i - O_i)^2]^{0.5}\} \bar{O}^{-1}$$

381 where  $n$  = number of observations,  $P_i$  and  $O_i$  are the simulated and observed  $i$ th value pair, and  $\bar{O}$   
382 is the observed mean. Normalizing with  $\bar{O}$  enables a comparison of the variability of parameters  
383 with widely different units and scales, such as ET rate and biomass accumulation, although  
384 admittedly, nRMSE fails for  $\bar{O} =$  zero or small values close to zero.

#### 385 2.2.4 *k-means clustering*

386 A *k*-means clustering algorithm was used to group models with similar nRMSE statistics and  
387 identify the top-performing models in a non-arbitrary way. Analyses focused on nRMSE for four  
388 pairs of model output variables, including simulated ET (ETs) versus grain yield and biomass  
389 from -10 to +20 days after planting (DAP) (soil E dominant) and from 41 to 100 DAP (canopy T  
390 dominant). Initial tests varied the number of clusters ( $n$ ) from 1 to 19. The final analysis was  
391 conducted with  $n=4$  clusters based on reducing the sum of squared distance from the cluster  
392 center to less than 20% of that for  $n=1$  cluster. Using  $n=4$  clusters also resulted visually  
393 appealing cluster plots with the set of top-performing models clearly identified within groups  
394 having low nRMSE for both variables of each pair. The *k*-means analysis was conducted using  
395 the “scikit-learn” package for Python (Pedregosa et al., 2011).

396

397

398 **3 Simulation results and discussion**

399 3.1 *Daily results for irrigated and rainfed Mead in 2003 (the driest year) and Bushland 100%*  
400 *and 75% sprinkler irrigations in 2013 (the year with highest observed ET rates)*

401 These four cases were selected from among the twenty treatment-years available for more  
402 detailed (daily) examination because they represent the two sites and the two cases at each site  
403 with the likely greatest water stress difference between treatments, i.e., irrigated versus rainfed in  
404 the driest year at Mead and 100% versus 75% MESA irrigation in the year with the highest daily  
405 ET rates in Bushland.

406 3.1.1 *Daily simulated evapotranspiration (ETs)*

407 3.1.1.1 *Irrigated Mead in 2003.* As found previously (Kimball et al., 2019), there was a wide  
408 range in ETs among the models (Fig. 1). However, the median of all the models tended to be  
409 close to the observed values most days. Admittedly, for this intercomparison, as well as for all  
410 the others that follow in the rest of this paper, the median is biased toward DSSAT because of  
411 the large number of “flavors.” For this case, the observed values fell within the short (1-3 mm/d)  
412 green boxes much of the time, which indicates many of the models produced respectable  
413 simulations. There was only a slight ( $< 1$  mm/d) improvement in model performance going from  
414 Phase 1 to Phase 4. It appears that the greatest variability and uncertainty among the models  
415 occurred from about 10 days before planting to 10 DAP (soil E dominated) and from about 130  
416 to 160 DAP (after the crop matured). A likely cause of the latter issue is that many models  
417 retained a fair amount of green LAI at and after simulated maturity; thus, model equations for ET  
418 that depend strongly on LAI did not result in sufficient termination of ET. Successive model  
419 adjustments or calibrations going from Phase 1 to Phase 4 as more information was provided  
420 only slightly improved this. Model code improvement is needed to decrease green LAI due to

421 senescence, eventually shutting down T at crop maturity. Code improvement likely is also  
422 needed to improve the simulation of bare soil ET.

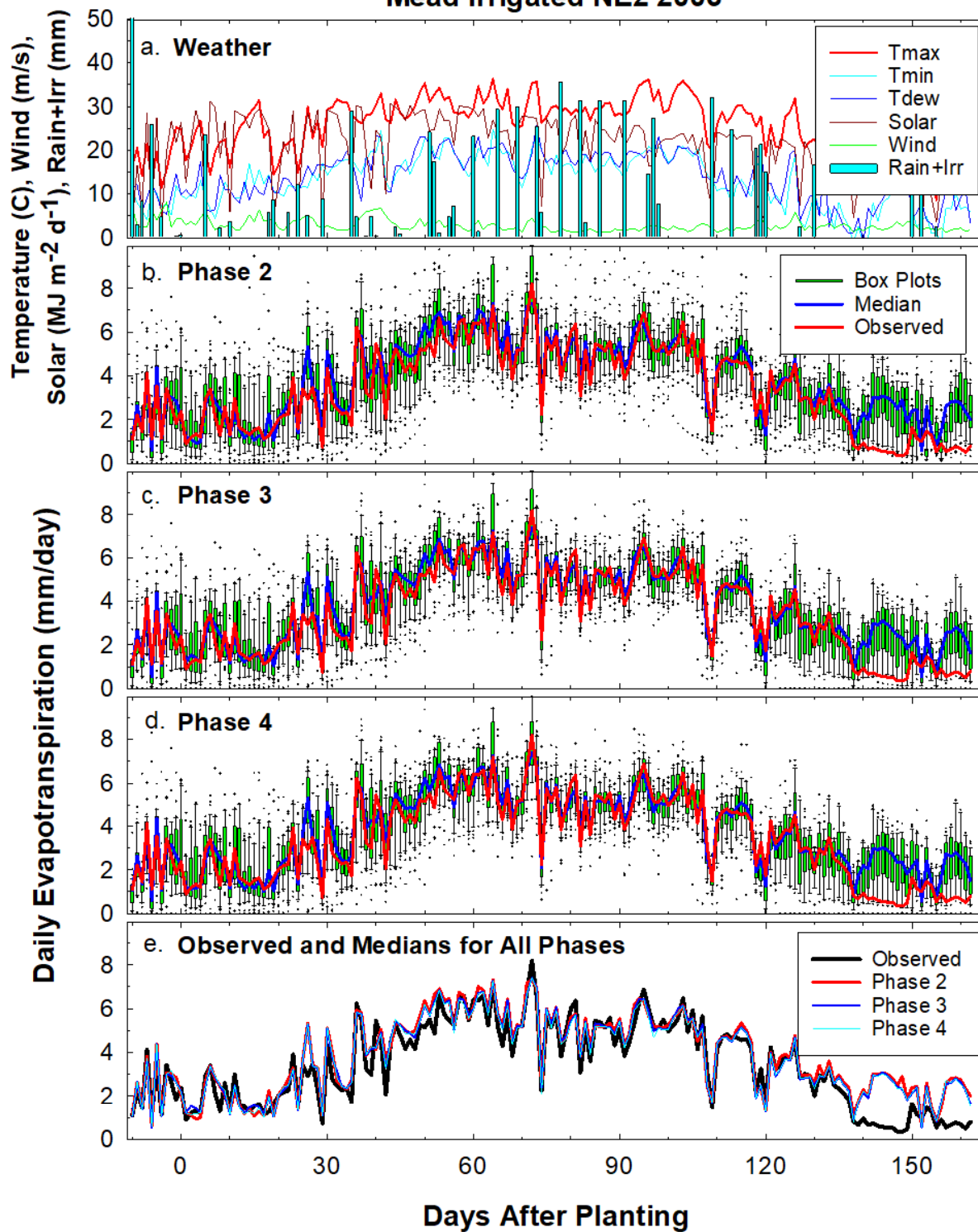
423 3.1.1.2 *Rainfed Mead in 2003*. For rainfed conditions at Mead, the models showed large  
424 variability (uncertainty) in daily ETs from about -10 to +10 DAP (soil E dominated; Fig. 2)  
425 similar to the irrigated field (Fig. 1). The greatest deviations (or errors) occurred from about 70  
426 to 95 DAP when there was little rainfall (Fig. 2a). The observed ET continued at close to 4  
427 mm/d, whereas the models simulated much lower rates. Like the irrigated field (Fig. 1), after  
428 DAP 120 as the crop matured, the measured ET decreased rapidly, whereas the models continued  
429 to simulate much higher ET. The ET variability during the -10 to +10 DAP period was related to  
430 highly different methods for simulating E, some of which proved to be less accurate. The issues  
431 during the maturation period after 120 DAP are related to the insufficient termination of T after  
432 maturity. More importantly, the period from about 70 to 95 DAP and beyond corresponds to the  
433 period of water limitation, when most models (and the median) simulated lower than observed  
434 ET. We suspect this is caused by inadequate soil water dynamics in the models, such as  
435 insufficient rooting depth, inadequate water up-flux or the presence of a perched water table, as  
436 well as excessive simulated ET during the early growth phase that depleted the simulated soil  
437 water too much, thus reducing ET later.

438

439

440

### Mead Irrigated NE2 2003

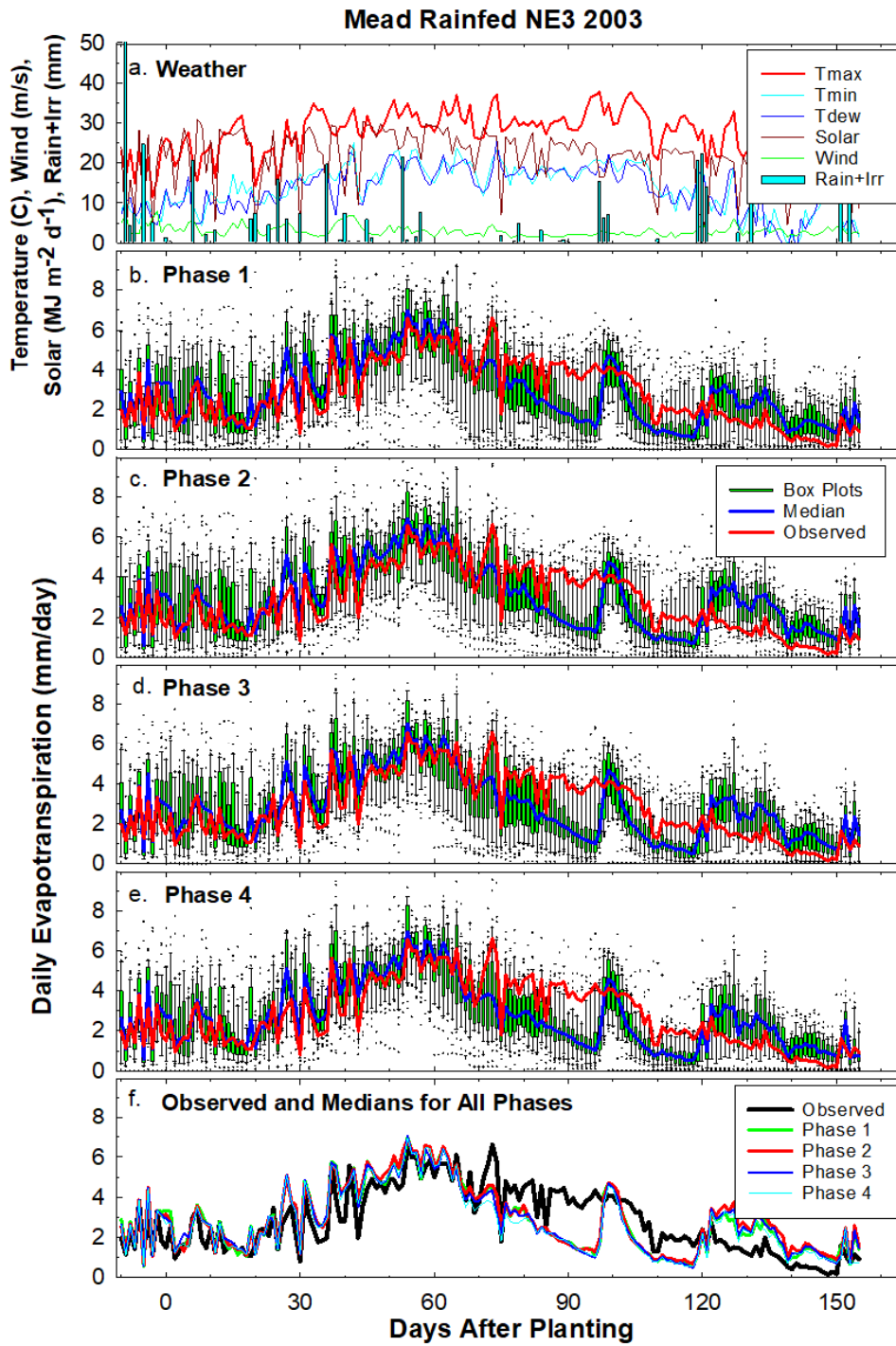


441

442

443 Figure 1. (a.) Weather variables (maximum and minimum air temperature, dew point, solar  
444 radiation, wind speed, rainfall) observed at irrigated field NE2 at Mead in 2003 versus days after  
445 planting (DAP). (b.) Box plots of daily simulated evapotranspiration (ETs) where the lower and  
446 upper limits of the box indicate the 25<sup>th</sup> and 75<sup>th</sup> percentile of ET values simulated by 41 maize  
447 growth models, respectively, the lower and upper whiskers indicate the 10<sup>th</sup> and 90<sup>th</sup> percentiles,  
448 and the points are outliers. Observed values and the median values from the 41 models are also  
449 shown. The simulated outputs start with Phase 2, for which the modellers were given leaf area  
450 index, growth, and grain yield data for all 100% irrigated treatment-years. Phase 1 simulations, a  
451 “blind” test whereby the modellers were only given weather, phenology, management, and soils  
452 information, are missing from this graph because a plant population mistake was made for Mead  
453 irrigated fields. (c.) Same as (b.) except for Phase 3 whereby the modellers were given the  
454 observed ET, soil water content, soil temperature for all 100% irrigated treatment-years. (d.)  
455 Same as (c.) except for Phase 4 whereby the modellers were given all data, including ET,  
456 growth, and grain yield, for all 20 treatment-years, including rainfed and 75% irrigations. (e.)  
457 Observed daily ET values as well as the median ETs values for Phases 2, 3, and 4





459

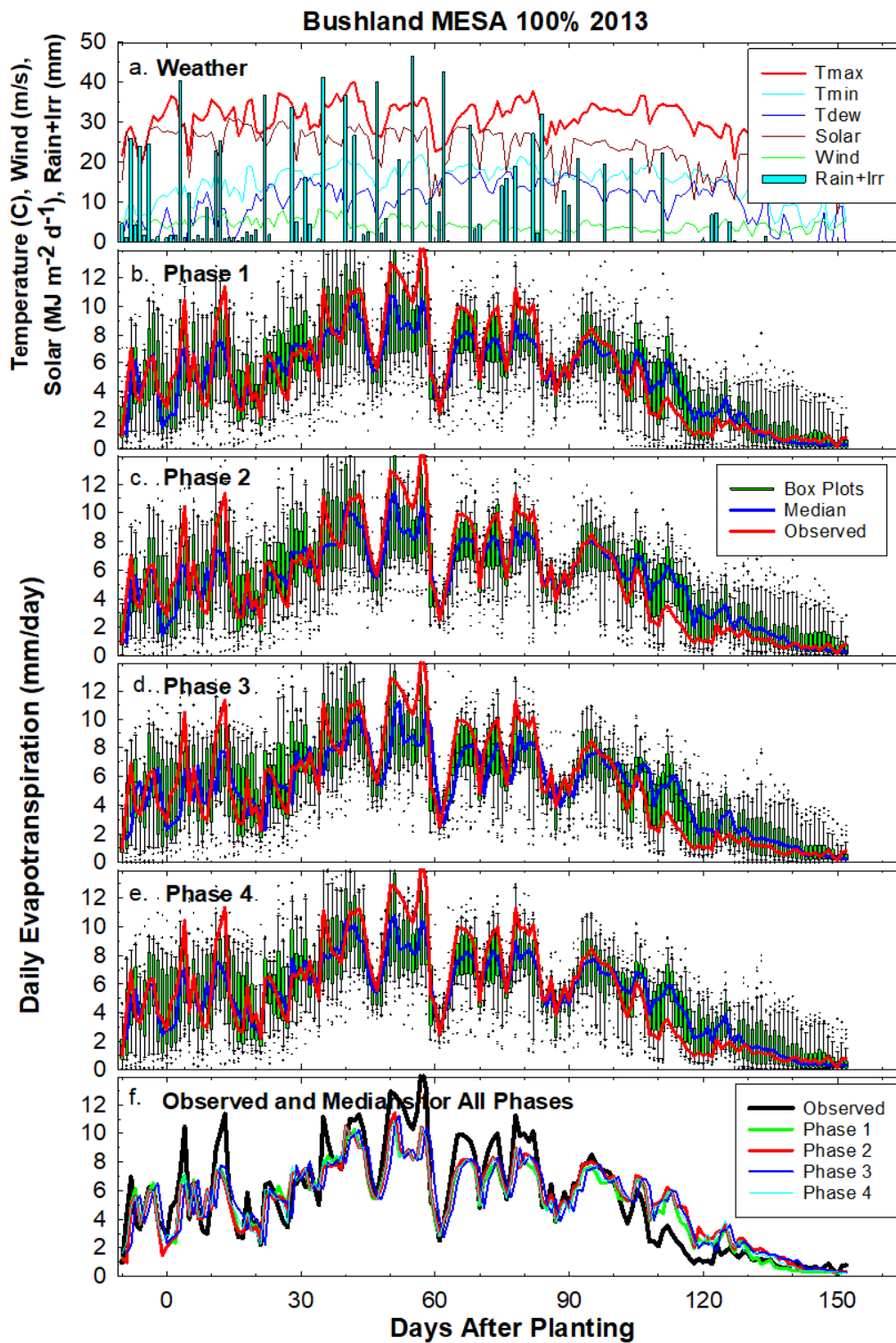
460 Figure 2. Similar to Figure 1 except for rainfed Mead field NE3 in 2003, and data for Phase 1 are  
 461 also included.

462

463

464 3.1.1.3 *100% and 75% irrigated Bushland in 2013*. For the Bushland location, most of the  
465 models (and the median) under-estimated ET during the 45 to 80 DAP period when windspeeds  
466 were high (> 5 m/s) and dew points were low (Figs. 3, 4). Model calibration (Phases 1 to 4) only  
467 partially improved this situation. This is possibly related to the fact that many of the models do  
468 not adequately account for varying wind speed and humidity, as can be deduced from the fact  
469 that the models estimated ET fairly well during periods of smaller ET but under-estimated ET  
470 greatly during periods of larger ET, when wind speeds were high and relative humidity was low.  
471 The fact that solar irradiance was also smaller during some of the periods of smaller ET (due to  
472 storm fronts) indicates that the radiation and energy balance algorithms may also need  
473 improvement. As before with Mead (Figs. 1, 2), the models failed to reduce T sufficiently after  
474 crop maturation (Figs. 3, 4; 105 to 145 DAP). Surprisingly, the models tended to simulate the  
475 75% irrigation treatment (Fig. 4) better than they did the 100% treatment (Fig. 3). Again, we  
476 speculate that this is because many of the models had not been calibrated previously to account  
477 for the very high winds and low humidity in Bushland, so their ETs simulations were lower than  
478 the high observed ET rates for the 100% irrigations treatment (Fig. 3), whereas under the 75%  
479 treatment (Fig. 4), drought stress reduced observed ET rates into the ranges for which the models  
480 had been calibrated. The fact that observed ET for the 75% MESA irrigations treatment was  
481 similar to that for the 100% SDI treatment (Evetts et al., 2019) indicates that E may play an  
482 important role in the discrepancies between simulated and observed ET for the 100% MESA  
483 treatment. The major difference between SDI and MESA irrigation in the Bushland experiments  
484 was the larger evaporative losses from the soil surface in MESA irrigated fields (Evetts et al.,  
485 2019).

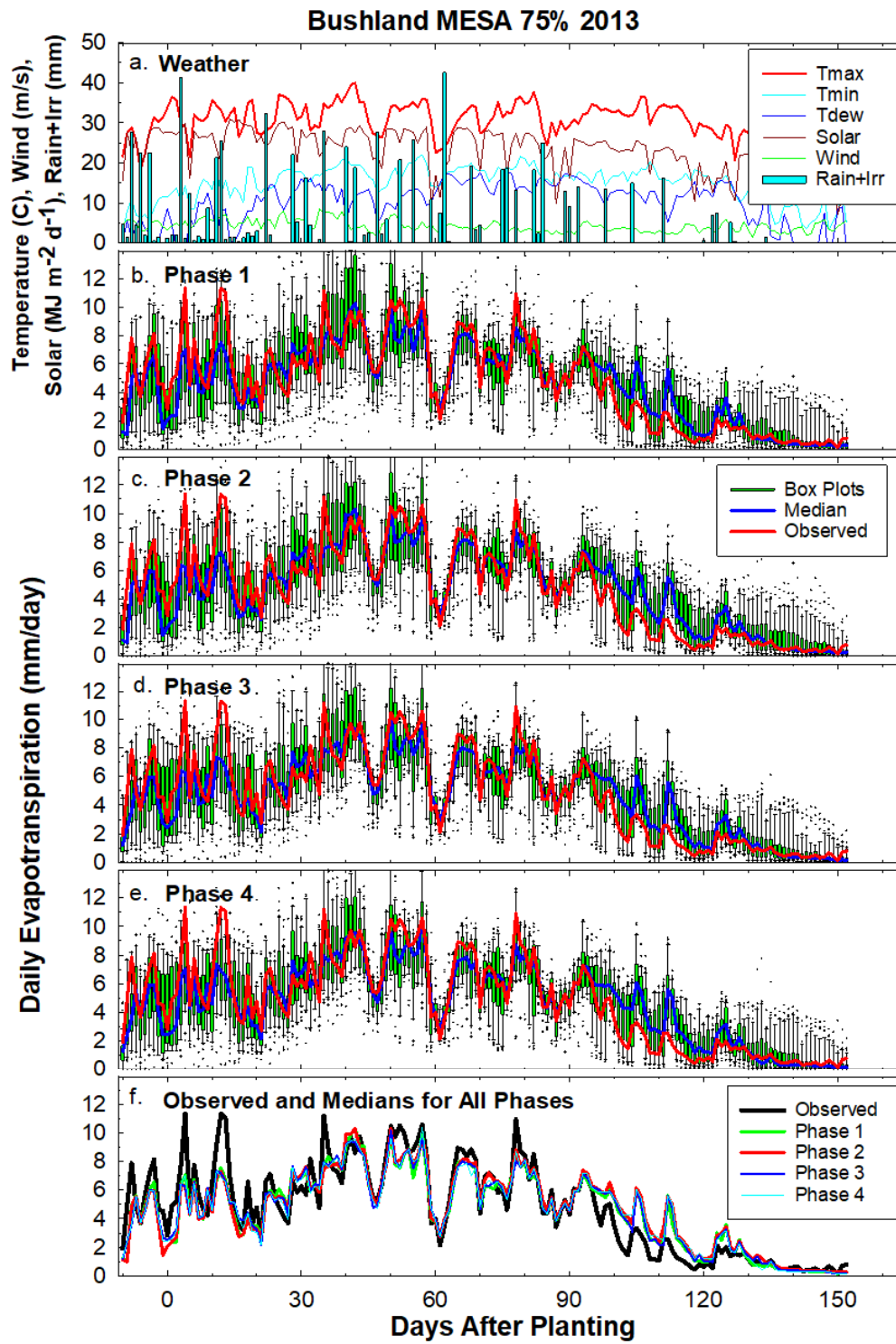
486



487

488 Figure 3. Similar to Fig. 1 except for 100% MESA (mid-elevation sprinkler application)  
 489 irrigation at Bushland in 2013.

490



491

492 Figure 4. Similar to Fig. 1 except for 75% irrigation at Bushland in 2013, and data for Phase 1  
 493 are also included.

494

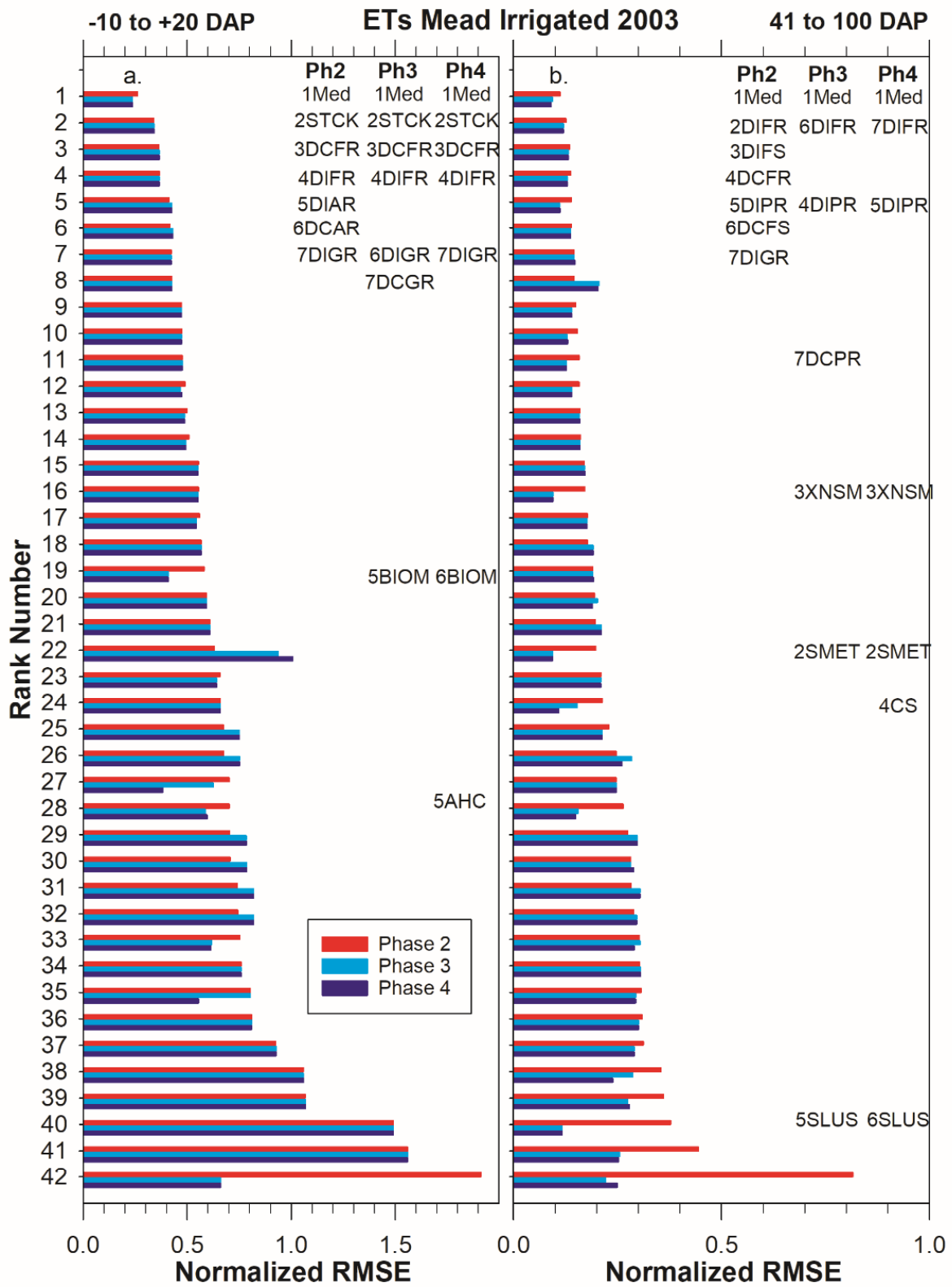
495 3.1.2 *Ranking of models with respect to their nRMSE for simulating daily ETs*

496 3.1.2.1 *Irrigated Mead in 2003*

497 The median of all the models had the lowest nRMSE for ETs for Phases 2, 3, and 4 for both early  
498 season (-10 to +20 DAP; soil E dominant) and mid-season (41 to 100 DAP; canopy T dominate)  
499 (Fig. 5). For early season STCK was the best model followed by several DSSAT “flavors,” and  
500 at mid-season several DSSAT flavors again did well, especially for Phase 2. STCK uses Penman  
501 (1948) to calculate atmospheric demand and the 2-phase model of Brisson and Perrier (1991) and  
502 Brisson et al. (1998, 2003) to calculate soil water evaporation,  $E_a$  (Table S1). Note that all the  
503 DSSAT flavors listed for -10 to +20 DAP end in “R”, which indicates that the soil E method of  
504 Ritchie (1972) was better than the more recent method of Suleiman and Ritchie (2003, 2004).  
505 However, for Phase 2 during the 41 to 100 DAP period DIFS and DCFS did well, but during this  
506 period canopy T was dominant, so soil E was relatively unimportant then.

507

508 The effects of changes made by the modelers going from phase to phase can also be seen in Fig.  
509 5. For example, BIOM was ranked 19<sup>th</sup> for Phase 2, -10 to +20 DAP but improved to 5<sup>th</sup> and 6<sup>th</sup>  
510 for Phase 3 and Phase 4, respectively. Like the well-performing DSSAT flavors, BIOM



512 Figure 5. (a) Normalized root mean squared error (nRMSE) between observed and simulated  
513 daily ET values from -10 to +20 days after planting (DAP)(mostly soil E) for the irrigated field  
514 NE2 at Mead in 2003 for all the models. Phases 2, 3, and 4 are identified by red, cyan, and blue  
515 bars with Phase 2 at the top and Phase 4 at the bottom of each group. Phase 1 data are missing  
516 from this graph because a plant population mistake was made for Mead irrigated fields. The  
517 models have been sorted in ascending order of nRMSE for Phase 2 from top to bottom of the  
518 graph with the rank numbers on the left axis indicating their ranking for Phase 2. The Median  
519 (Med) and the six best models (lowest nRMSE) for Phase 2 are listed under “Ph2”. Somewhat  
520 similarly, the Median and six best models for Phases 3 and 4 are also listed under “Ph3” and  
521 “Ph4”, but because the modelers made different adjustments going from phase to phase, their  
522 rank order changed, so the names along with their nRMSE rank are in different positions down  
523 the graph. (b) Same as for (a) except the data are for 41 to 100 DAP (mostly crop canopy T) with  
524 the ranking done on the 41 to 100 DAP Phase 2 data

525

526 also uses Ritchie (1972) to simulate soil E. AHC rose from 28<sup>th</sup> to 5<sup>th</sup> from Phase 2 to Phase 4  
527 for the -10 to +20 period. AHC uses the two-stage FAO-56 method to simulate E for mostly bare  
528 soil (Table S1). A huge improvement was made by SLUS going from 40<sup>th</sup> for Phase 2 to 5<sup>th</sup> for  
529 Phase 3 for the 41 to 100 DAP period. SLUS calculates atmospheric demand from Priestly and  
530 Taylor (1972) and then uses an empirical equation to simulate potential ET<sub>p</sub> (Table S1), which  
531 would be mostly T for the irrigated full canopy. XNSM, SMET, and CS all markedly improved  
532 from Phase 2 to Phase 4 to be among the best for the full canopy (Fig. 5b). All three use FAO-56  
533 (Allen et al., 1998) with some modifications (Table S1).

534

### 535 3.1.2.2 *Rainfed Mead in 2003*

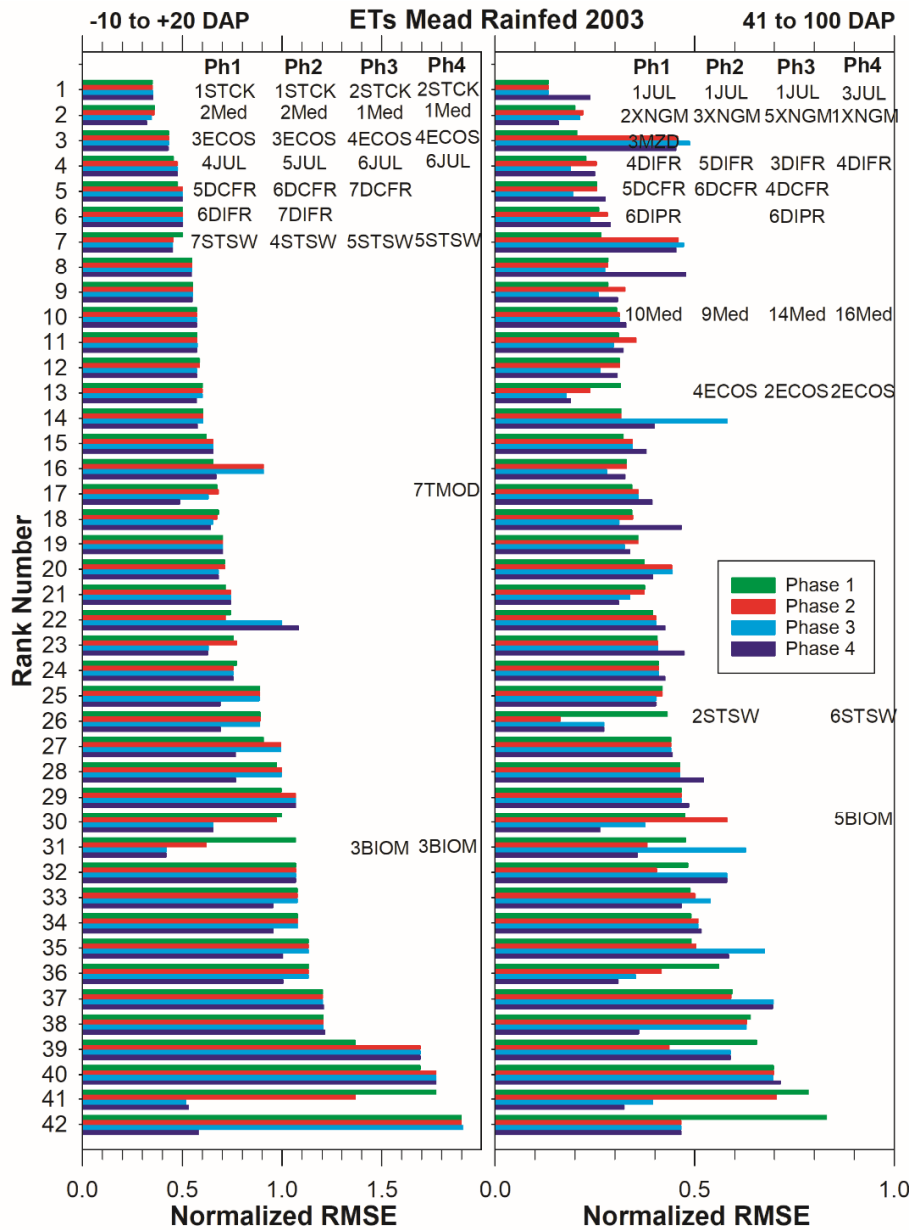
536 The STCK model was best for simulating ETs for the -10 to +20 DAP period in the rainfed field  
537 at Mead in 2003 for Phases 1 and 2, while the median was 2<sup>nd</sup>, and then they traded rankings for  
538 Phases 3 and 4 (Fig. 6a). ECOS, JUL, DCFR, DIFR, and STSW also did very well. ECOS is a  
539 full energy balance model while JUL uses the Penman-Monteith approach (Monteith, 1965) with  
540 a 10-layer canopy (Table S1). BIOM rose from 31<sup>st</sup> for Phase 1 to 3<sup>rd</sup> for Phases 3 and 4. JUL  
541 and XNGM were best for the 41 to 100 DAP period (Fig. 6b). MZD was 3<sup>rd</sup> for Phase 1, but did  
542 much worse in the other phases. DIFR, DCFR, and DIPR did well. ECOS rose from 13<sup>th</sup> for  
543 Phase 1 to 2<sup>nd</sup> for Phases 3 and 4. All of these listed models were better than the median for this  
544 case.

545

### 546 3.1.2.3 *100% MESA irrigation at Bushland in 2013*

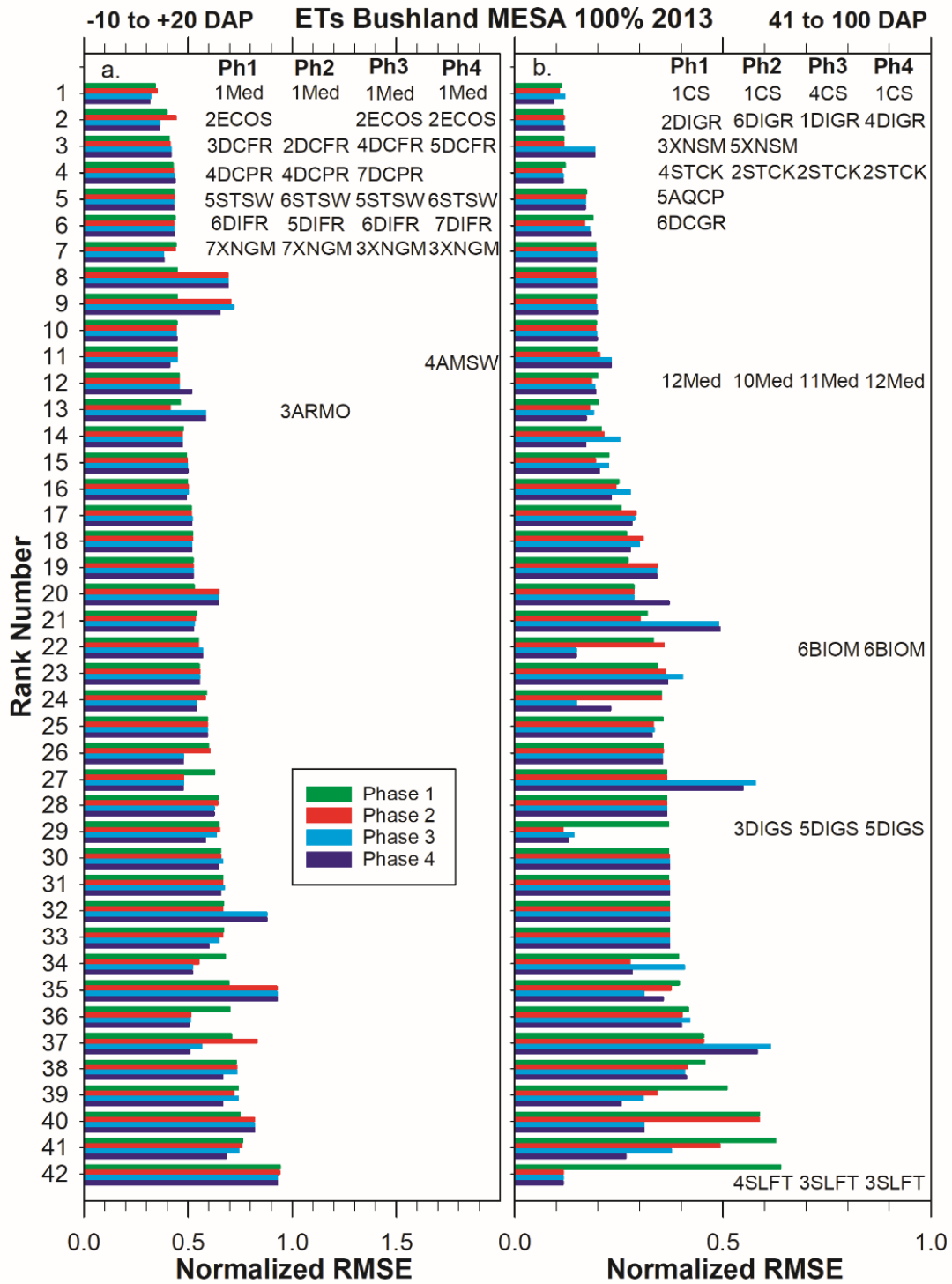
547 The median of all the models ranked 1<sup>st</sup> at simulating ETs from -10 to +20 DAP for all phases in  
548 Bushland with 100% MESA irrigation in 2013 (Fig. 7a). Except for Phase 2, ECOS, an energy





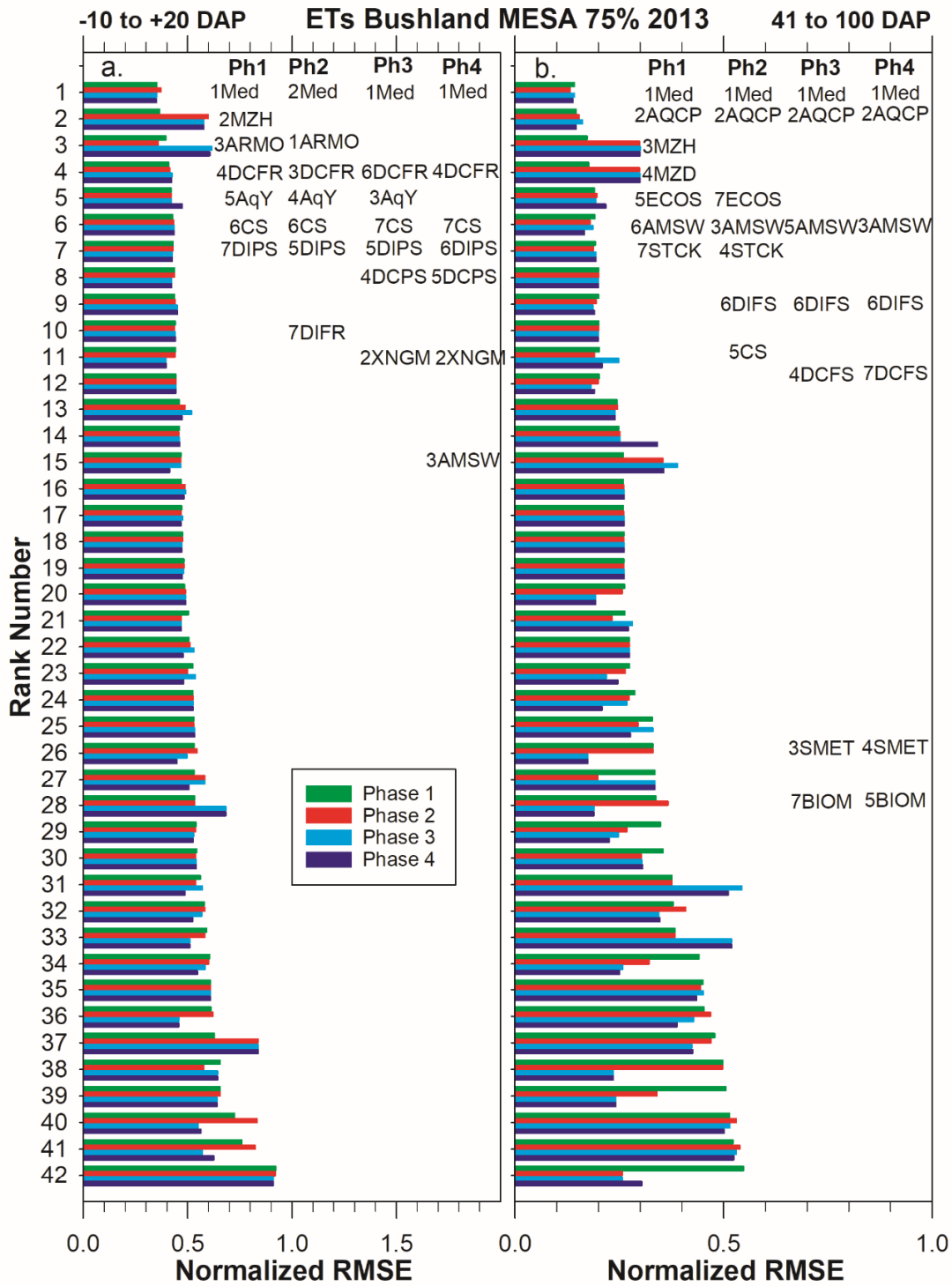
549

550 Figure 6. (a.) Normalized root mean squared error (nRMSE) between observed and simulated  
 551 daily ET values from -10 to +20 days after planting (DAP)(mostly soil E) for the rainfed field  
 552 NE3 at Mead in 2003 for all the models. Phases 1, 2, 3, and 4 are identified by green, red, cyan,  
 553 and blue bars with Phase 1 at the top and Phase 4 at the bottom of each group. The models have  
 554 been sorted in ascending order of nRMSE for Phase 1 from top to bottom of the graph with the  
 555 rank numbers on the left axis indicating their ranking for Phase 1. The Median (Med) and the six  
 556 best models (lowest nRMSE) for Phase 1 are listed under “Ph1”. Somewhat similarly, the  
 557 Median and six best models for Phases 2, 3 and 4 are also listed under “Ph2”, “Ph3”, and “Ph4”,  
 558 but because the modelers made different adjustments going from phase to phase, their rank order  
 559 changed, so the names along with their nRMSE rank are in different positions down the graph.  
 560 (b.) Same as for (a.) except the data are for 41 to 100 DAP (mostly crop canopy T).



562

563 Figure 7. Like Fig. 6 except for 100% MESA (mid-elevation sprinkler application) irrigation to  
 564 restore soil water to field capacity at Bushland.



565

566

567 Figure 8. Like Fig. 6 except for the MESA (mid-elevation sprinkler application) 75% irrigation  
 568 at Bushland.

569

570 balance model was best. DCFR, DCPR, STSW, DIFR, and XNGM all did well. At mid-season  
571 (41 to 100 DAP, Fig. 7b), CS, DIGR, and STCK did well for all phases. BIOM and DIGS  
572 improved greatly for phases 3-4. However, the median was only about 12<sup>th</sup>.

573

#### 574 3.1.2.4 75% MESA irrigation at Bushland in 2013

575 The median of all the models was 1<sup>st</sup> for all but one phase for both early season (-10 to +20  
576 DAP) and mid-season (41 to 100 DAP) for the 75% irrigation treatment at Bushland in 2013  
577 (Fig. 8). MZH was ranked 2<sup>nd</sup> for Phase 1, early season (Fig. 8a) but then did much worse for  
578 other phases. Similarly, ARMO did well for Phases 1 and 2, but then did much worse. DCFR,  
579 CS, and DIPS did well in all phases. XNGM, AMSW, and DCPS were among the best for Phase  
580 4. AMSW uses a transpiration efficiency to compute ETs from biomass accumulation, XNGM  
581 uses a modified Penman-Monteith (Monteith (1965), and DCPS uses Priestly and Taylor (1972)  
582 to simulate potential atmospheric demand and ultimately ETs.

583

584 At mid-season, AQCP and AMSW did well for all phases (Fig. 8b). MZH and MZD did well for  
585 Phase 1, but then much worse for later phases. DIFS, DCFS, SMET, and BIOM did well for  
586 Phases 3 and 4.

587

#### 588 3.1.2.5 Intercomparison among the models for all four cases of daily ET for Phase 4

589 Looking at Figs. 5-8, no single model appears among the best (lowest nRMSE) six for all four  
590 cases. The median was among the best for the all four cases from -10 to +20 DAP (mostly E),  
591 but only for two cases from 41 to 100 DAP (mostly T). Focusing on the -10 to +20 periods  
592 (mostly E), DCFR was among the best for 3 cases; STCK, DIFR, BIOM, ECOS, STSW, SNGM,

593 and AMSW for 2 cases; and DIGR, JUL, TMOD, CS, DIPS, DCPS for 1 case. For the 41 to 100  
594 DAP periods, the median was among the best only twice. BIOM was best for 3 cases; DIFR, CS,  
595 and SMET were best for 2 cases; and STCK DIGR, ECOS, JUL, STSW, XNGM, DIPR, XNSM,  
596 SLUS, DIGS, SLFT, AQCP, AMSW, DIFS, and DCFS were all among the best for 1 case.  
597 BIOM stands out as being the only model to be among the best twice for early season (mostly E)  
598 and thrice for midseason (mostly T).

599

## 600 3.2 *Inter-comparisons within the DSSAT family*

### 601 3.2.1 *Daily ETs*

602 A comparison of E methods within the DSSAT models, revealed that the older Ritchie-2-stage  
603 model (Ritchie, 1972) was consistently better (lower nRMSE and lower simulated ETs) than the  
604 Sulieman and Ritchie method (2003, 2004) during the -10 to +20 DAP period, regardless of the  
605 other ET methods (Figs. 9a, 10a). The Ritchie-2-stage method was also better (slightly lower  
606 nRMSE) for ETs in the 41 to 100 DAP full canopy phase (Figs. 9b, 10b) for two reasons (less E  
607 during that phase, but mostly because lower early E allowed soil water in deeper layers to be  
608 conserved for the 41 to 100 DAP period, thus contributing more to T during the latter phase).

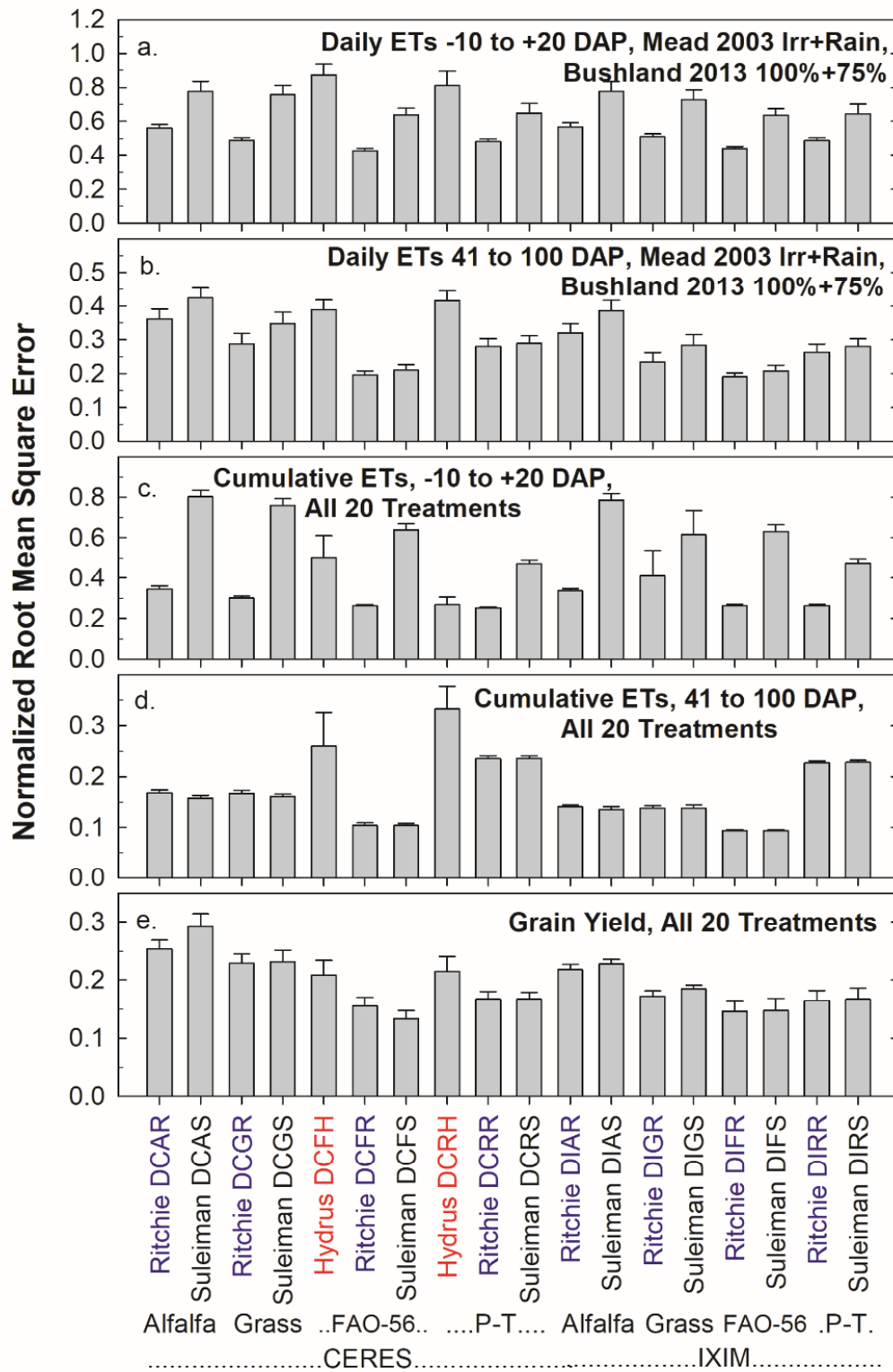
609

610 In spite of having a theoretically more realistic mechanism for moving soil water with potential  
611 gradients, the Hydrus method (Šimůnek et al., 1998, 2008; Shelia et al., 2018) did not perform  
612 as well as the more empirical Ritchie (1972) and Sulieman and Ritchie (2003, 2004) methods  
613 (Fig. 9a, 9b). However, Hydrus was just recently incorporated into the DSSAT shell, whereas the  
614 Ritchie (1972) and the Sulieman and Ritchie (2003, 2004) routines have been used for many  
615 years and likely have been fine-tuned to the system. Also, Hydrus is very sensitive to the values

616 of the soil physical and hydraulic properties, so if those parameter values were off, the simulated  
617 ET would also be off.

618

619 A comparison of potential ET (ET<sub>p</sub>) methods within the DSSAT models illustrated that the  
620 FAO-56 method (in present DSSAT; Allen et al., 1998) with K<sub>can</sub> of 0.62 (gives K<sub>ep</sub> = 0.50)  
621 performed better (lower nRMSE) for ETs than the other ET<sub>p</sub> methods: Priestley-Taylor (P-T;  
622 1972), alfalfa reference-[ET<sub>r</sub>, ASCE equation (Allen et al., 2005)], or grass reference-[ET<sub>o</sub>,  
623 ASCE equation (Allen et al., 2005)] during both the -10 to +20 DAP period and the 41-100 DAP  
624 period (Figs. 10a, 10b). K<sub>can</sub> is the extinction coefficient for absorption of photosynthetically-  
625 active radiation by LAI, while K<sub>ep</sub> is the extinction coefficient for absorption of total solar  
626 energy by LAI. The default K<sub>can</sub> for CERES is 0.85 (in the ecotype file). K<sub>can</sub> was reduced to  
627 0.62

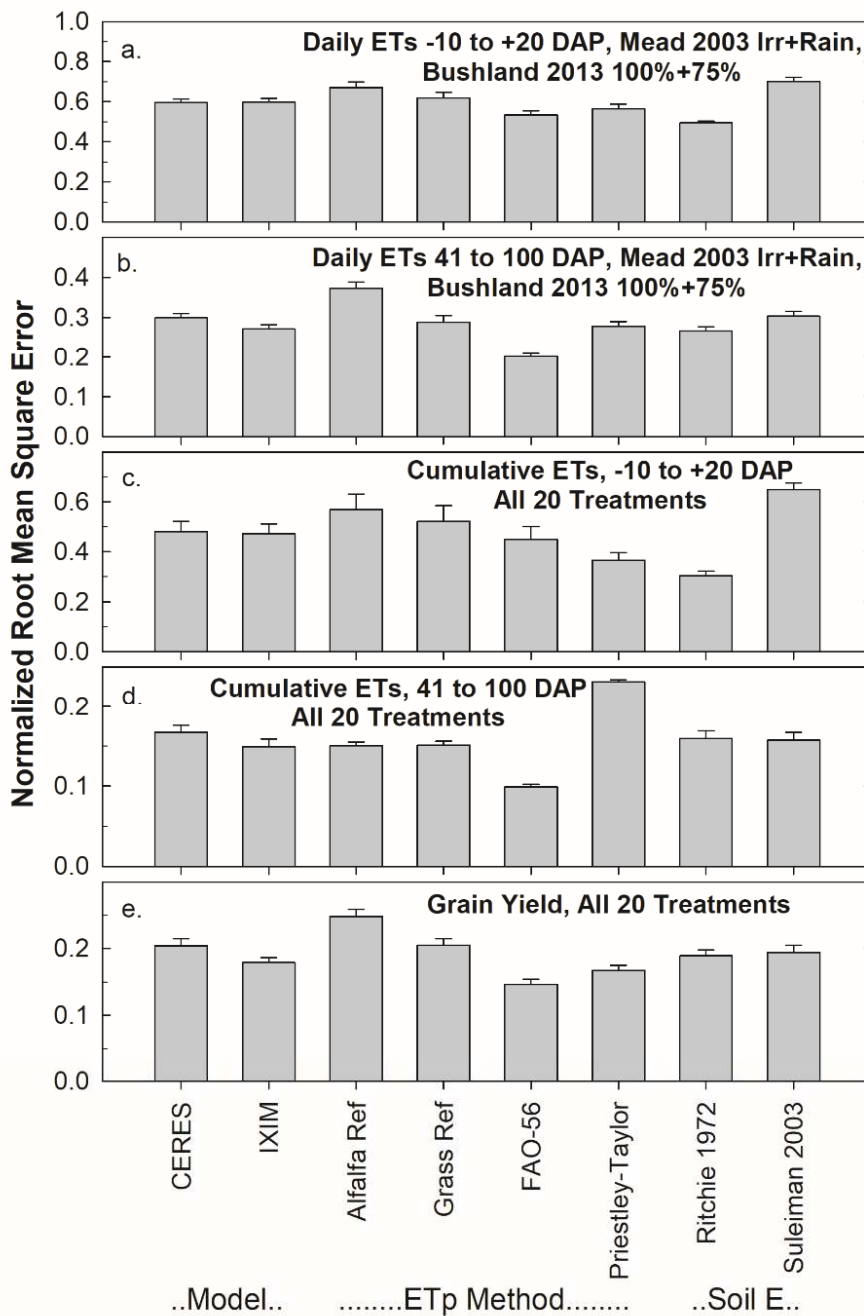


628

629

630 Figure 9. Normalized root mean square errors (nRMSE) of the 18 “flavors” of the DSSAT family  
631 models (a) for the -10 to +20 DAP periods (mostly soil E) of daily ETs over all phases for the  
632 irrigated and rainfed data for Mead 2003 and the 100% and 75% MESA irrigated data for  
633 Bushland 2013. Models included are DSSAT CSM-CERES and DSSAT CSM-IXIM, whose  
634 horizontal names span the corresponding left ten and right eight vertical bars, respectively.  
635 Potential ET<sub>p</sub> calculation methods are using alfalfa (tall, ET<sub>r</sub>) and grass (short, ET<sub>o</sub>) reference  
636 crop coefficients with the ASCE standardized reference equation (Allen et al., 2005), FAO-56  
637 (Allen et al., 1998), and Priestley-Taylor (1972). These horizontal names span the corresponding  
638 bars above them. Soil evaporation calculation methods follow Ritchie (1972; labelled  
639 “Ritchie”), Suleiman and Ritchie (2003, 2004; labelled just “Suleiman”), and Hydrus (Šimůnek  
640 et al., 1998, 2008; Shelia et al., 2018; labelled “Hydrus”). (b) Like (a) except for the 41 to 100  
641 DAP periods. (c.) The values plotted are averages (+ standard errors) of the nRMSEs for Phase 4  
642 for all 20 treatment-years of the cumulative ETs from -10 to +20 DAP periods. (d.) Like (c.)  
643 except for the cumulative ETs from 41 to 100 DAP. (e.) nRMSEs for Phase 4 grain yields for all  
644 20 treatments.  
645





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Figure 10. Direct comparisons using the same data as for Fig. 9 (excluding Hydrus) between the DSSAT-CERES and DSSAT-IXIM models, among the four potential ET methods, and between the two soil water evaporation methods for the corresponding a, b, c, d, and e graphs. The horizontal “Model”, “ETp Method”, and “Soil E” labels span the corresponding bars above.

655 during phase 3, which reduces the effective energy extinction from 0.685 to 0.50 [latter value  
656 supported lysimeter studies of Villalobos and Fereres (1990), as well as the theory of foliar  
657 absorption of total solar energy (Goudriaan, 1977)]. The  $K_{ep}=0.50$  was used for P-T as well. On  
658 the other hand, the alfalfa reference-FAO-56, or grass reference-FAO-56 are dual-coefficient  
659 methods that compute their own coefficients during incomplete and full canopy phases of ET. In  
660 contrast to a previous study on cotton (*Gossypium hirsutum* L.) ET (Thorp et al., 2020), the  
661 methods based on ASCE alfalfa and grass reference ET did not perform as well as DSSAT FAO-  
662 56 and P-T; however, the calibration methodology limited their comparability in the present  
663 study. It appears that the newly reduced  $K_{ep}$  of 0.50 contributed to improved DSSAT  
664 performance, and it is an improvement over the default DSSAT value. As mentioned previously,  
665 Sau et al. (2004) reported that the FAO-56 with a  $K_{ep}=0.50$  gave the best simulations of ET, soil  
666 water extraction, and biomass accumulation with the CROPGRO-Faba bean model for a water-  
667 limited environment. FAO-56 was better than P-T, and the extinction coefficient ( $K_{ep}=0.50$ ) was  
668 better than a higher  $K_{ep}$  for either ET method. Similarly, Lopez-Cedron et al. (2008) found the  
669 CERES model gave better simulations of maize biomass, grain yield, and harvest index under  
670 water-limited environments, using FAO-56 rather than P-T, and again,  $K_{ep}$  of 0.50 was better  
671 than a higher energy extinction coefficient (default in CERES was 0,685).

672

673 There was no significant difference in nRMSE between the CERES or IXIM models for the -10  
674 to +20 DAP period (Fig. 10a, soil E dominant), whereas for the 41 to 100 DAP period (Fig. 10b,  
675 canopy T dominated), IXIM was slightly better, likely because of its more realistic simulation of  
676 LAI progression. IXIM senesces green leaf area more rapidly (and more mechanistically) near

677 maturity than does CERES, which results in less T during the grain-filling phase, and which  
678 more closely matches the observed reduction in T.

679

680 Comparing methods for calculating potential evapotranspiration (ET<sub>p</sub>) on the nRMSE of ETs for  
681 the 41 to 100 days after planting (DAP) period (Fig. 10b), the FAO-56 method had significantly  
682 lower nRMSE. For the -10 to +20 DAP period (Fig. 10a), it was better than both the alfalfa (tall;  
683 *Medicago sativa* L.) and grass (short) crop coefficients with the ASCE standardized reference  
684 equation, but Priestley-Taylor (P-T) tended to be almost as good. Comparing soil E methods,  
685 Ritchie (1972) was much better than Suleiman and Ritchie (2003, 2004) for the -10 to +20 DAP  
686 period (Fig. 10a) soil E dominant), and Ritchie (1972) was slightly better even for the 41 to 100  
687 DAP period (Fig. 10b, canopy T dominant).

688

### 689 3.3 Inter-comparisons within the STICS, Expert-N, and MAZSIM families

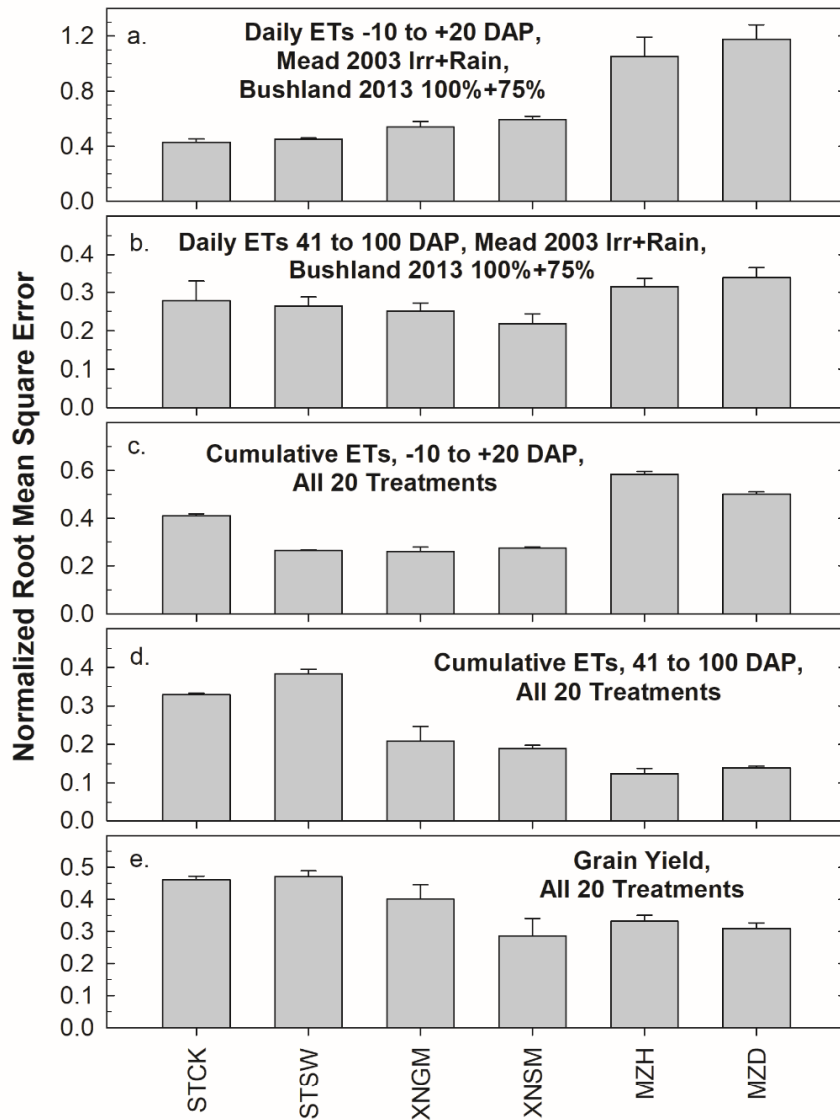
690 Comparing the nRMSE of daily ETs between the two “flavors” of each pair of the STICS,  
691 Expert-N, and MAZSIM families, there were no significant differences (Figs. 11a, 11b). STCK  
692 uses a single surface model (Penman, 1948) to compute potential ET<sub>p</sub>, whereas STSW handles  
693 separate canopy and soil surfaces (Shuttleworth and Wallace, 1985), Thus, for these four cases,  
694 STCK and STSW performed equally well at simulating soil E (Fig. 11a) and canopy T (Fig. 11b)  
695 in spite of the different methods for simulating ET<sub>p</sub>. Both XNSM and XNGM models use  
696 Penman-Monteith based approaches for simulating ET<sub>p</sub>. However, XNSM follows FAO 56  
697 guideline based on E<sub>T0</sub> multiplied with a single crop factor to get ET<sub>p</sub> while in XNGM the  
698 required surface- and aerodynamic resistances are calculated directly from simulated LAI and  
699 simulated canopy height. In addition, XNGM follows the more detailed Farquhar model in

700 simulating photosynthesis and leaf T but simplifies vertical root distribution. The latter could  
701 possibly explain slightly better soil moisture simulations of XNSM compared to XNGM (data  
702 not shown). In XNSM, temperature, moisture, and nutrient availability in different soil layers are  
703 taken into account when simulating rooting depth and root length distribution. In contrast,  
704 XNGM assumes a uniform distribution of root length density within the rooted zone, with the  
705 increase in rooting depth simply simulated from the increase in root biomass, regardless of the  
706 soil conditions. Thus, considering that there are marked differences between the two models, it is  
707 surprising that they differ so little in their ability to simulate ETs. The lack of significant  
708 differences between MZD and MZH is reasonable because they are the same in their  
709 representation of plant and soil processes. Both models run on an hourly time step internally but  
710 MZD takes daily weather data as input and interpolates them into hourly time steps, while MZH  
711 takes hourly weather data directly as input.

712

### 713 *3.4 Potential ET<sub>p</sub> and other sources of variability/error in daily ETs*

714 There was a wide variability among the models in their simulated values for daily ETs as shown  
715 in Figs. 1-4, which is similar to the previous results reported by Kimball et al. (2019). In that  
716 report, Fig. 10 shows that much of the variability can be attributed to variability among the  
717 models in their values of ET<sub>p</sub>. Therefore, for this study we requested more values of “upstream”  
718 variables that the modelers might be using to compute ET<sub>p</sub>, including reference ET based on  
719 short (12 cm) grass (ET<sub>o</sub>), reference ET based on tall (50 cm) alfalfa (ET<sub>r</sub>), soil coefficient (K<sub>s</sub>),  
720 basal crop coefficient (K<sub>cb</sub>), soil evaporation coefficient for drying soil (K<sub>e</sub>), overall crop  
721 coefficient (K<sub>c</sub>), potential soil evaporation (E<sub>p</sub>), potential transpiration (T<sub>p</sub>), ET<sub>p</sub>, and of course,



722

723 Figure 11. Direct comparisons using nRMSE between the STCK and STSW flavors of the  
 724 STICS model family, between XNGM and XNSM flavors of Expert-N family, and between the  
 725 MZH and MZD flavors of the MAZSIM model for (a) the -10 to +20 DAP time period (mostly  
 726 soil E). The data used were all phases for the irrigated and rainfed data for Mead 2003 and the  
 727 100% and 75% MESA irrigated data for Bushland 2013. (b). Like (a) but for the 41 to 100 DAP  
 728 period (mostly canopy T). (c.) Phase 4 of cumulative ETs from -10 to +20 DAP for all 20  
 729 treatments. (d) Like (c) but for cumulative ETs from 41 to 100 DAP. (e) Phase 4 grain yield for  
 730 all 20 treatment-years.

731 ETs. Three of the models did not report  $ET_p$ , presumably the energy balance ones that do not use  
732 the concept.

733 Focusing on the Phase 2 results from irrigated Mead in 2003, 34 models reported  $E_p$  and 35  
734 models reported  $T_p$ , and both  $E_p$  and  $T_p$  were quite variable (data not shown). As expected, the  
735 magnitude and variability of the soil  $E_p$  were greatest for bare soil at the beginning of the season.  
736 However, there was more than a 2 mm/day spread even at mid-season. Surprisingly, a few of the  
737 models showed some  $T_p$  starting on the day of planting before the plants had even emerged.  
738 Then, as the  $T_p$  increased in magnitude as plants grew to full size by mid-season, so did the  
739 range in variability among them, similar to ETs.

740

741 Thirteen of the models reported  $E_{To}$  and only 4 reported  $E_{Tr}$ . Presumably  $E_{To}$  and  $E_{Tr}$  depend  
742 only on weather, yet  $E_{To}$  varied by a factor of about 2 at midseason among the 13 models (data  
743 not shown). Apparently, several different definitions and equations for  $E_{To}$  are in play among  
744 these models.

745

746 Only 6, 4, 4, and 7 models used  $K_s$ ,  $K_{cb}$ ,  $K_e$ , and  $K_c$ , respectively. It seems likely that more  
747 models do use them, but they are computed and not routine output, so the modelers would have  
748 had to change code to get them. In any event, there appear to be several ways that models are  
749 getting from  $E_{To}$  (or  $E_{Tr}$ ) to  $ET_p$  that are contributing to the variability of ETs.

750

751 Thus, in conclusion, the variability in  $ET_p$  and ETs appears to be coming from steps all along the  
752 way starting from the calculations of  $ET_p$  to the final resultant ETs.

753

754 3.5 *Cumulative month to whole season ETs results for all 20 treatment-years*

755 The previous sections focused on the daily ET for four selected treatment-years. However, one  
756 can imagine that an underestimate of simulated daily ET one day could save some simulated soil  
757 moisture and lead to an overestimate the next day. The following sections examine the  
758 cumulative ET over longer time periods to reveal the extent that the errors are also cumulative.

759

760 3.5.1 *ETs from -10 to +20 DAP (mostly soil E) and 41 to 100 DAP (mostly canopy T)*

761 Moving from daily ETs for the four cases (2003 for irrigated and rainfed Mead; 2013 MESA at  
762 75% and 100% irrigation at Bushland) to cumulative ETs over longer time durations for all 20  
763 treatment-years also showed wide variability among the models (Fig. 12). Again, there were  
764 variations by factors of 2 to more than 4 among them in cumulative ETs from -10 to +20 DAP  
765 (mostly soil E) (Fig. 12a). There was little or no improvement in going from Phase 1 to Phase 4.  
766 For Treatments 1-10 for Mead, the medians of the models were close to the observations, but for  
767 Treatments 11 and 12, the models generally overestimated ETs. For Bushland, most of the  
768 models underestimated Treatment 13 when spray irrigation wetted the surface and Treatment 18  
769 when rainfall wetted the surface of SDI fields. Most models overestimated Treatments 17 and 19  
770 when the SDI field surface was dry despite plentiful irrigation, but the medians were close to  
771 observed for the other 4 treatments. These results indicate problems simulating E from wetted  
772 surfaces and with simulated redistribution of water from buried drip lines to the surface (too  
773 much water movement to the surface).

774

775 Looking at cumulative ETs from 41 to 100 DAP (mostly canopy T), there is a range of about a  
776 factor of 2 among the models (Fig. 12b), which is bad but less than that from the bare soil (Fig.

777 12a). For Mead, most of the models overestimated ETs for Treatments 1-6 and 8-11. They  
778 underestimated Treatment 7 but were close for Treatment 12. For Bushland, most of the models  
779 underestimated ETs under sprinkler irrigation for Treatments 14-16, which represent wetter soil  
780 Ranking the models' ability to simulate cumulative ETs from -10 to +20 DAP by nRMSE (Fig.  
781 13a), the medians were close to observations for Phases 2-4. SLFT was the best model for Phases  
782 2 and 3 and was next best in Phase 4. SLFT uses FAO-56 (Allen et al., 1998) to calculate  
783 atmospheric demand and then dual crop coefficients simulate ETs (Table S1). For Phase 2,  
784 models in the DSSAT family were ranked 3-7, and several did well in Phases 3 and 4. AMSW  
785 was best in Phase 4. CS and XNGM were among the best in Phases 3 and 4.

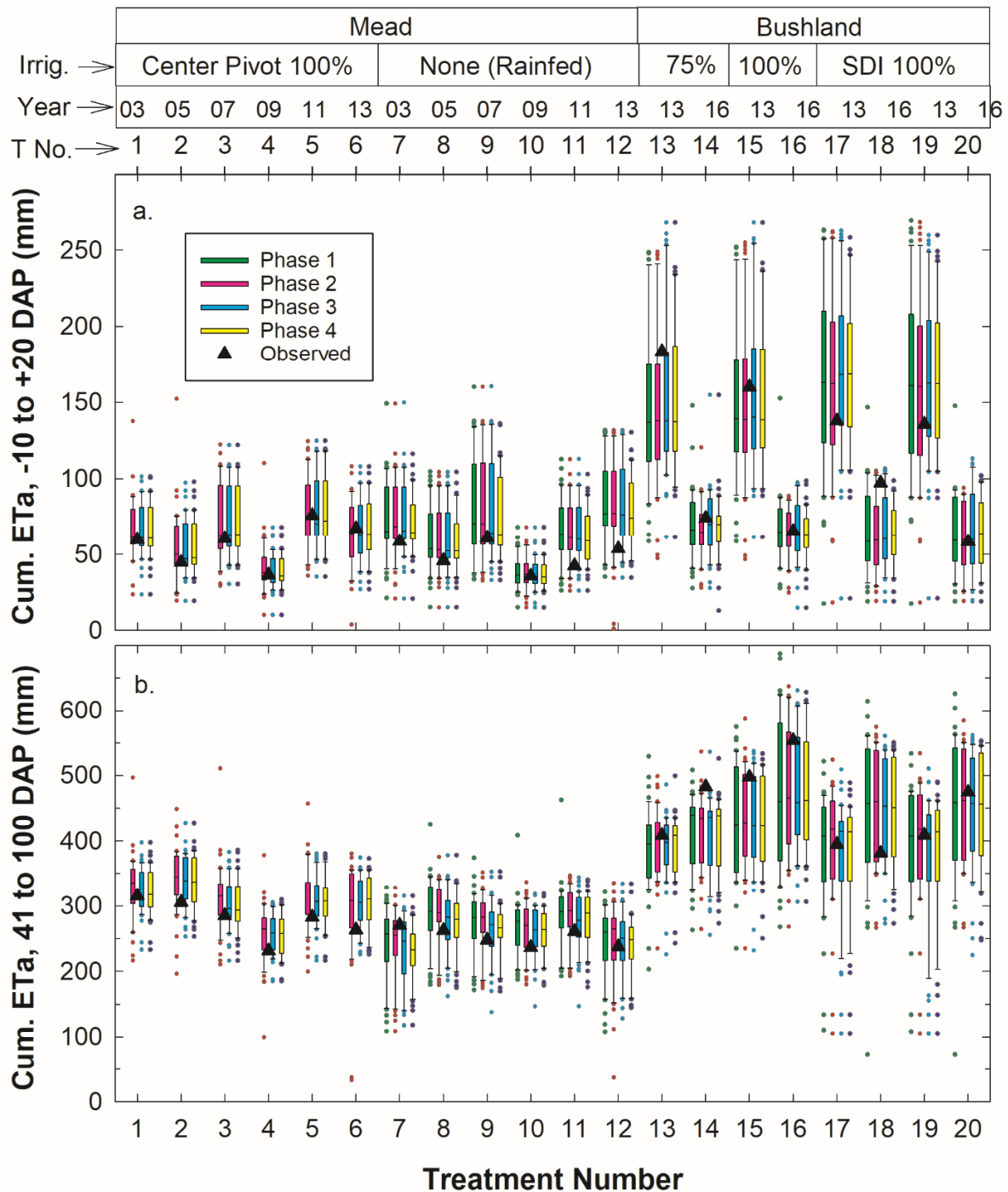
786

787 Similarly ranking their ability to simulate ETs from 41 to 100 DAP (Fig. 13b), several of the  
788 models in the DSSAT family did well for Phases 2, 3, and 4. ECOS was among the best for  
789 Phases 2 and 3. SSMi (which uses Priestly and Taylor (1972) for potential atmospheric demand  
790 and transpiration efficiency with biomass accumulation to simulate ETs) was ranked 6 for Phases  
791 3 and 4, and SMET was ranked 3<sup>rd</sup> for Phase 4. surface conditions, but the medians were close  
792 for Treatment 13. Under SDI irrigation, most models underestimated Treatment 18, but the  
793 medians were close for Treatments 17, 19, and 20.

794

795





796

797 Figure 12. Box plots for all 20 treatment-years (as defined at the top) of cumulative simulated  
 798 evapotranspiration (ETs) over (a) the -10 to +20 days after planting (DAP) time period (mostly  
 799 E) and (b) the 41 to 100 DAP time period (mostly T) for all four phases. The dark lines across  
 800 the boxes indicate the medians of all the models. Also shown are the corresponding observations.  
 801 Phase 1 is not shown for treatments 1-6 because of a planting density mistake.  
 802

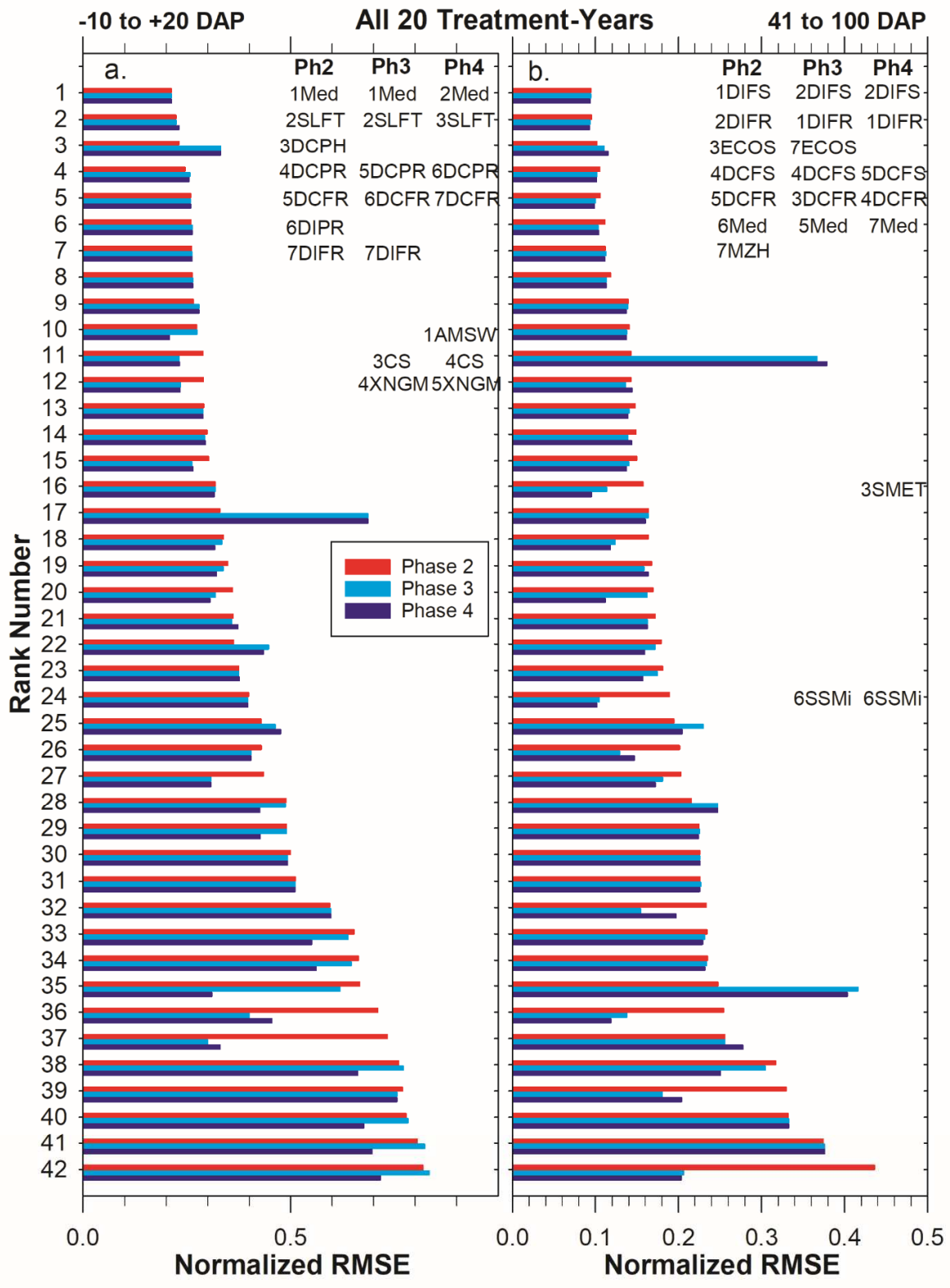
803 Looking back at Section 3.1.2.5, BIOM was among the best at simulating daily ETs, yet it was  
804 not among the best at simulating ETs over the longer intervals. On the other hand, DIFR was  
805 almost as good as BIOM for simulating daily ETs, and it was best for simulating cumulative ETs  
806 over the 41 to 100 DAP periods (Fig. 13, Phase 4). Besides DIFR, DCFS and SMET were the  
807 only other two models that were among the best for cumulative ETs over the 41 to 100 DAP  
808 periods and also were among the best for at least one case of daily ETs. For the -10 to +20 DAP  
809 periods, DCFR, XNGM and CS are the only models that were best for simulating cumulative  
810 ETs and also for daily ETs at least for one case. Thus, doing well for simulating daily ETs did  
811 not guarantee success at simulating cumulative ETs.

812

### 813 *3.5.2 Inter-comparisons of cumulative ETs within the DSSAT and other model families*

814 There were wide differences in performance among model “flavors” within the DSSAT family  
815 for cumulative simulated ETs from -10 to +20 DAP (mostly soil E) over the 20 treatment-years  
816 (Fig. 9c). Most obvious is that the Ritchie (1972) soil E method did much better than the  
817 corresponding Suleiman (Suleiman and Ritchie, 2003, 2004) method for every case. The Hydrus  
818 method did comparatively well for this cumulative-ETs/20-treatment-year comparison, which is  
819 in contrast to the daily-ETs/4-treatment-year comparison in Fig. 9a.

820



822 Figure 13. (a.) Normalized root mean squared error (nRMSE) between observed and simulated  
823 cumulative ET values from -10 to +20 days after planting (DAP)(mostly soil E) for all 20  
824 treatment-years for all the models. Phases 2, 3, and 4 are identified by red, cyan, and blue bars  
825 with Phase 2 at the top and Phase 4 at the bottom of each group. The models have been sorted in  
826 ascending order of nRMSE for Phase 2 from top to bottom of the graph with the rank numbers  
827 on the left axis indicating their ranking for Phase 2. The Median (Med) and the six best models  
828 (lowest nRMSE) for Phase 2 are listed under “Ph2”. Somewhat similarly, the Median and six  
829 best models for Phases 3 and 4 are also listed under “Ph3”, and “Ph4”, but because the modelers  
830 made different adjustments going from phase to phase, their rank order changed, so the names  
831 along with their nRMSE rank are in different positions down the graph. Phase 1 is not shown  
832 because of the planting density error for the six irrigated Maize treatment-years. (b.) Same as for  
833 (a.) except the data are for 41 to 100 DAP (mostly crop canopy T).  
834

835 As would be expected, looking at the 41 to 100 DAP periods, the soil E method had little effect  
836 (Fig. 9d). However, Hydrus, did poorly which is in contrast to the -10 to +20 periods (Fig. 9c).

837

838 There was no significant difference in performance between the CERES Maize and IXIM Maize  
839 models for the -10 to +20 DAP periods (Fig. 10c), whereas IXIM was slightly better than  
840 CERES for the 41 to 100 DAP periods (Fig. 10d). The better performance of IXIM for full  
841 canopy conditions was likely because of its more realistic simulation of LAI progression, as  
842 mentioned previously. Priestley-Taylor was the best ETp method for the -10 to +20 DAP periods  
843 (Fig. 10c) but worst for the 41 to 100 DAP periods (Fig. 10d). FAO-56 was second best for -10  
844 to +20 DAP periods (Fig. 10c) but best for the 41 to 100 DAP periods (Fig. 10d). As was  
845 obvious from Fig. 9c, the direct comparison between Ritchie (1972) and Suleiman and Ritchie  
846 (2003) in Fig. 10c, confirms the superiority of the older Ritchie (1972) method for simulating  
847 soil E, likely because the Suleiman and Ritchie overestimates the upward movement of soil  
848 water from deeper depths. However, under full canopy conditions (Fig. 10d), there was no  
849 difference between the two soil E methods.

850

851 Looking at other models with more than one flavor, STSW performed better than STCK for  
852 cumulative ETs from -10 to +20 DAP (Fig. 11c), but the reverse was true from 41 to 100 DAP  
853 (Fig. 11d). It is somewhat surprising that the two-surface method for computing ETp in STSW  
854 did better for the -10 to +20 DAP period when there was only the single soil surface, but was  
855 worse for the 41 to 100 DAP full canopy period. However, looking more closely, both models  
856 did well for both time periods for the Mead data, whereas for Bushland in 2013, both models had  
857 trouble getting emergence with SDI in 2013, and this issue distorted the results. There was no

858 significant difference between XNGM and XNSM for either of the time periods (Figs. 11c, 11d).  
859 As noted in section 3.3, the two models use slightly different variants of the Penman-Monteith  
860 approach and differing root distribution approaches resulting in essentially no differences in  
861 daily ETs for the four cases (Figs 11a, 11b) nor in cumulative ETs for all 20 treatments (Figs.  
862 11c, 11d). MZD did slightly better than MZH for the -10 to +20 DAP periods (Fig. 11c), but  
863 there was little difference for 41 to 100 DAP (Fig. 11d). Any differences between MZD and  
864 MZH are likely associated with the differences between interpolated and measured hourly  
865 weather data that were driving MZD and MZH, respectively.

866

867 *3.6 Ability of the models in Phase 4 to simulate agronomic parameters for all 20 treatment-years*  
868 *– maximum leaf area index, biomass at about 40 DAP and about 100 DAP, and final*  
869 *grain yield.*

870 *3.6.1 Considering all the models*

871 There was a wide range in simulations of maximum LAI between the lowest and the highest  
872 models (Fig. 14a). However, for some treatments, most of the models agreed closely as indicated  
873 by short boxes. Indeed, for Treatments 1 and 3, most of the models agreed almost exactly with  
874 one another and with observations. For many treatments, the medians agreed closely with  
875 observations. However, for Treatments 4 and 14, the models mostly underestimated LAI,  
876 whereas for Treatments 11, 15, and 17, they mostly overestimated LAI. For Bushland, treatments  
877 15, 17, and 19 were in the 2013 year that began quite dry and required plentiful irrigation to  
878 achieve germination and to support crop growth. Overestimation of LAI may be linked to model  
879 algorithms overreacting to the plentiful irrigation in an otherwise stressful year.

880

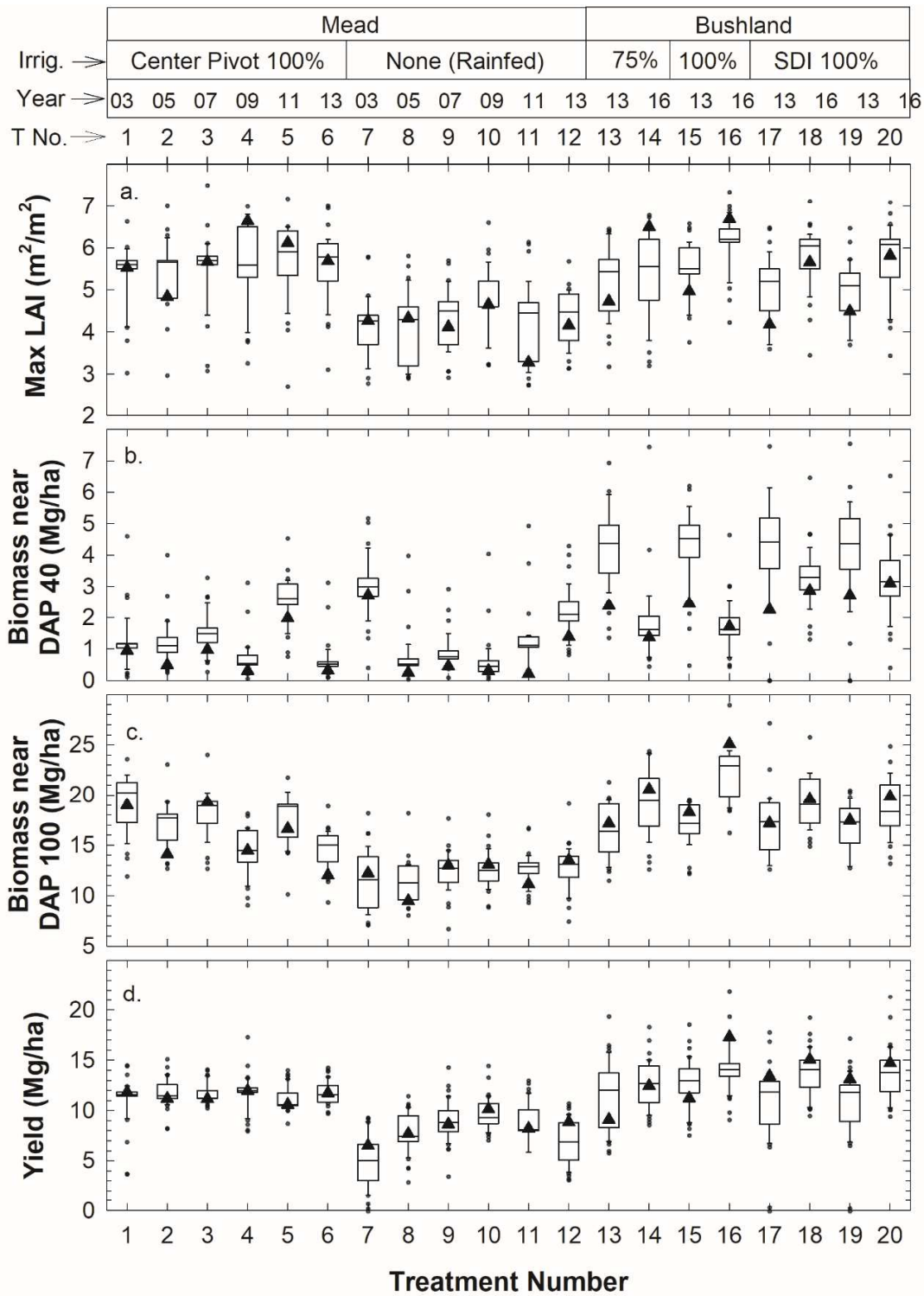
881 Most of the models overestimated above-ground biomass at about 40 DAP for almost all the  
882 treatments (Fig. 14b). This was particularly true for the dry 2013 year at Bushland, again  
883 indicating that the plentiful irrigation caused the models to overestimate biomass accumulation  
884 despite an otherwise stressful environment. However, by 100 DAP (Fig. 14c), most of the  
885 models did much better, and agreement with observations was much closer. For final grain yield,  
886 most of the models did surprisingly well (Fig. 14d). For the irrigated Mead data (Treatments 1-  
887 6), most of the models agreed with one another and with the observations. They also did well for  
888 four of the Mead rainfed years, but underestimated Treatments 7 and 12. They did less well with  
889 the Bushland data, especially underestimating the SDI irrigation grain yields. The  
890 underestimation of SDI grain yields is likely tied to overly large partitioning of applied water to  
891 soil E, leaving less available water for T and grain yield formation. Many models, including  
892 DSSAT, lack true SDI capability and applied the water to the soil surface in this study. Because  
893 SDI was more efficient in water use than the MESA irrigation method in the actual fields used  
894 for this study (Evetts et al., 2020) and, therefore, likely will be more widely used in the future, the  
895 inability to handle SDI is an emerging lacuna in many of the models that should be addressed in  
896 future.

897

### 898 *3.6.2 Inter-comparisons of grain yield within the DSSAT and other model families*

899 DCFS was the best of the several model flavors within the DSSAT family to simulate grain  
900 yield, as indicated by nRMSE for Phase 4 (Fig. 9e). However, general patterns are not obvious in  
901 Fig. 9e. Nevertheless, some patterns emerge from a direct comparison in Fig. 10e. IXIM was  
902 slightly better than CERES. FAO-56 emerged as the best ETp method followed by Priestly-  
903 Taylor and then ASCE standardized reference ET equation with grass (short, 12 cm) crop

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907 Figure 14. Box plots for Phase 4 of (a) maximum leaf area index, (b) biomass at about 40 days  
 908 after planting (DAP), (c) biomass at about 100 DAP, and (d) final grain yield for all 20  
 909 treatment-years. Also shown are the corresponding observations (triangles).



910  
911 coefficients and then alfalfa coefficients (tall, 50 cm) (Fig. 10e), which might be somewhat  
912 biased because they were not independently calibrated. There was no significant difference in the  
913 ability to simulate grain yield between the two methods for simulating soil E.

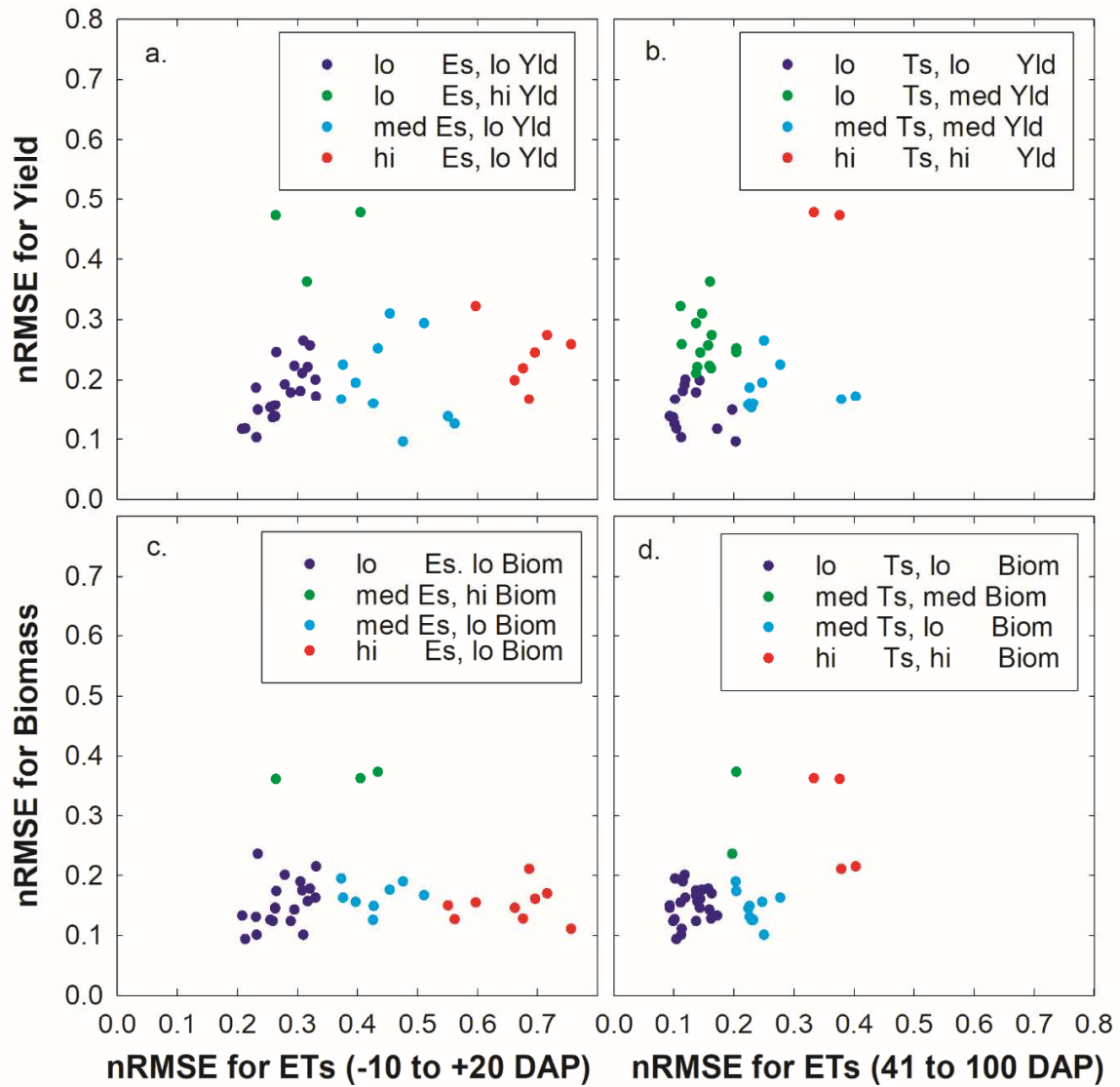
914  
915 There was little difference in grain yield simulation ability between the two flavors of the STICS  
916 model or of the MAZSIM model (Fig. 11e). However, XNSM tended to be better than XNGM,  
917 although XNGM uses a “more physiological” approach to simulate growth based on the  
918 principle of functional balance, in contrast to XNSM, in which a more or less predetermined  
919 scheme is used for partitioning of photosynthates.

920

### 921 *3.7 K-means clusters*

922 In Figs. 15a and 15c the nRMSE of simulated grain yields for 40 of the models (plus their  
923 medians) and of simulated biomass accumulation for 39 of the models (plus their medians),  
924 respectively, are compared against the nRMSE of the simulated cumulative ETs for the -10 to  
925 +20 DAP time period (which was mostly Es for these mostly bare soil conditions). These graphs  
926 show that for many of the models the relative errors for simulating ETs tended to be larger than  
927 those for biomass and grain yield, which is consistent with the survey of Seidel et al. (2018) who  
928 found that few modelers calibrate the ET aspects of their models. Further, k-means clustering  
929 analyses with the number of clusters (k) specified to be four, the models were grouped into the  
930 four clusters illustrated in Figs. 15a and 15c. As can be seen, the k-means program identified a  
931 cluster of models that did quite well with the nRMSE for grain yields and biomass less than

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933

934 Figure 15. (a.) K-means clusters of the nRMSE for grain yields of 41 models (plus their median)  
 935 for all 20 treatments versus the corresponding ETs for -10 to +20 DAP (mostly Ea). (b.) Same as  
 936 (a) but for the 41 to 100 DAP periods (mostly Ta). (c.) K-means clusters of the nRMSE for  
 937 biomass accumulation of 40 models (plus their median) from 41 to 100 DAP versus the  
 938 corresponding ETs for from -10 to +20 DAP (mostly Ea). (d.) Same as (c) but for the 41 to 100  
 939 DAP periods (mostly Ts). (Note: one of the 41 models did not simulate grain yield and two did  
 940 not simulate biomass.)

941

942 about 0.25 and that for ETs less than 0.35. One of the other clusters did poorly at simulating  
943 grain yield and biomass, and the other two clusters did progressively worse at simulating ETs.  
944 Figs. 15a and 15c suggest that a model's ability to simulate ETs well early in the growing season  
945 from -10 to +20 DAP can carry on through the seasons to help simulate biomass and grain yields  
946 well too.

947

948 Similarly, Figs. 15b and 15d illustrate the nRMSEs for grain yield and biomass against the  
949 nRMSE for the cumulative ETs from 41 to 100 DAP, when there were mostly full crop canopies.  
950 Comparing Fig. 15b with 15a and comparing Fig. 15d with 15c, it is apparent that the models  
951 were better at simulating the cumulative ETs for the full canopies than they were for bare soil at  
952 the beginning of the growing seasons. Again, k-means cluster analyses identified clusters of  
953 models that did quite well at simulating grain yields, biomass, and full canopy ETs quite well  
954 with the nRMSE of grain yield, biomass, and ETs all less than about 0.2. It is not surprising that  
955 there is such a cluster of models that can simulate ETs well during midseason which aids them to  
956 also simulate biomass and grain yields well.

957

958 Table 2 lists the models included in the best-performing clusters in Fig. 15. There is overlap  
959 among the four categories, but CS, AMSW, ECOS, XNSM, and AHC all excelled enough to  
960 appear in all four. Similarly performing well enough to appear in all four categories are three  
961 flavors from the DSSAT family: DIFR, DCFR, and DIGR. Not surprisingly, the ensemble  
962 median did very well, being first or second in all the categories, consistent with previous inter-  
963 comparisons, e.g., Asseng et al. (2015). Among these eight models, CS, XNSM, AHC, DIFR,  
964 DCFR, and DIGR all use FAO-56 (Allen et al., 1998) to compute ET<sub>p</sub> (Table S1). ET<sub>o</sub> was used

965 as ET<sub>p</sub> for DIFR and DCFR, whereas DIGR used crop coefficients to adjust ET<sub>o</sub> to ET<sub>p</sub> and  
966 then various simulated or calculated crop or energy extinction coefficients were used to obtain  
967 ETs. AMSW simulates T using the transpiration efficiency approach and E using Ritchie's  
968 (Ritchie, 1972) two-stage method (Probert et al., 1998; Keating et al., 2003). ECOS simulates  
969 ETs from net radiation that is partitioned into latent, sensible, and soil heat fluxes with energy  
970 balances on the canopy and soil surfaces approach (Grant et al., 2007; Grant and Flanagan,  
971 2007). DIGR uses the ASCE Standardized "Short Crop" (12-cm grass) ET<sub>o</sub> (Allen et al., 2005),  
972 which is a successor to FAO-56, with maize crop coefficients computed from simulated LAI to  
973 adjust ET<sub>o</sub> to ET<sub>p</sub>. Thus, six of these models have similar core approaches for simulating ETs  
974 but differ in other ways such as partitioning to leaf area or soil moisture movement, etc. AMSW  
975 and ECOS are both unique in their own ways within this elite group. The three DSSAT models  
976 all use the Ritchie-two-stage method for soil water evaporation rather than the Sulieman method,  
977 highlighting the need for E methods with improved upward movement of soil water and more  
978 accurate E loss in the incomplete canopy phase.

979  
980 However, something all eight models have in common is that they all have been widely used for  
981 a long time under a wide range of conditions. This includes the lesser-known XNSM because it  
982 is a hybrid model with elements from both the CERES model (Jones and Kiniry, 1986) and the  
983 SUCROS model family (van Laar, 1992; Wang and Engel, 2000). AHC is also included because  
984 it was developed based on a coupling of the significantly modified SWAP model (van Dam et  
985 al., 1997) and the EPIC crop growth model (Williams et al., 1989). Thus, there has been time for  
986 several generations of modelers to improve these models so that they perform well over a wide  
987 range of climatic and soil conditions.

988

989

990 Table 2. Lists of models in Fig. 15 identified as being in the K-means clusters of best models  
 991 (lowest nRMSE) for Phase 4 for simulated grain yields and biomass versus lowest nRMSE for  
 992 simulated ETs for -10 to +20 DAP (mostly bare soil, Es) and 41 to 100 DAP (mostly closed  
 993 canopy, Ts). The models are ranked according to their sums of nRMSE for grain yield or  
 994 biomass plus that for ETs.

995

Ranking	Yield vs. Es	Yield vs. Ts	Biomass vs Es	Biomass vs Ts
1	AMSW	Med	CS	Med
2	Med	CS	Med	CS
3	CS	AMSW	DCFS	DCFR
4	XNGM	SLFT	DIFR	SWB
5	DCFR	DCPR	DIFS	DCFS
6	DIFR	DCFR	DCFR	DIFR
7	DCPR	DIPR	SSMi	DIFS
8	SLFT	DIFR	AMSW	DIGR
9	DIPR	SLUS	ECOS	MZH
10	DIGR	DIGR	DACT	AHC
11	XNSM	DCGR	XNSM	DIGS
12	ECOS	BIOM	DIGR	DCGS
13	DCPH	XNGM	AHC	DIAR
14	BIOM	DIAR	DIGS	SSMi
15	DCGR	XNSM	XNGM	DCGR
16	AQCP	AQCP		MZD
17	AHC	AHC		AMSW
18	DIAR	ECOS		ECOS
19	SLUS	DCAR		DIAS
20	DCAR	DCRH		AQCP
21				XNSM
22				TMOD
23				DCAS
24				DCAR

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997

998 **4. Conclusions with discussion**

- 999 4.1 Like the previous maize model ET inter-comparison (Kimball et al., 2019), again there was  
1000 wide variability among the models in their ability to simulate ET, both on daily and on  
1001 longer interval bases. The variability generally persisted even as the modelers received more  
1002 information going from one phase to another, although a few modelers did make  
1003 performance improvements.
- 1004 4.2 Being among the best models at simulating daily ETs did not guarantee that a model would  
1005 be among the best at simulating cumulative ETs.
- 1006 4.3 Nevertheless, eight models, as well as the ensemble median, were identified that did well at  
1007 simulating (a) cumulative ETs from -10 to +20 DAP (mostly soil E), (b) cumulative ETs  
1008 from 40 to 100 DAP (mostly canopy T), (c) biomass accumulation, and (d) final grain yield.  
1009 The models were CS, AMSW, ECOS, XNSM, AHC, DIFR, DCFR, and DIGR. Six of them  
1010 follow the general approach of using FAO-56/Penman-Monteith (Allen et al., 1998, 2005)  
1011 to simulate ETs, while AMSW uses a transpiration efficiency approach (Probert et al., 1998;  
1012 Keating et al., 2003), and ECOS uses an energy balance approach (Grant et al., 2007; Grant  
1013 and Flanagan, 2007). All of these models or their ancestors have been in existence and have  
1014 been widely used for a long time. Thus, there has been time for improvement over a wide  
1015 range of climatic and soil conditions. Unlike the previous inter-comparison (Kimball et al.,  
1016 2019), none of the simpler models were among the best at simulating all four variables for  
1017 this study involving a wider range of environmental conditions from two locations.
- 1018 4.4 Although the ensemble median was not among the best estimates of soil moisture  
1019 (Supplementary), it was at the top or close to the top for all other categories. That the

1020 ensemble median generally outperforms any individual model is consistent with previous  
1021 intercomparisons, e.g., Asseng et al. (2015).

1022 4.5 Within the DSSAT family, the older Ritchie (1972) approach for simulating soil E was  
1023 markedly better than the newer Suleiman and Ritchie (2003, 2004) approach, which  
1024 appeared to overestimate upward movement of soil moisture.

1025 4.6 Further, within the DSSAT family, the FAO-56 (Allen et al., 1998) method for calculating  
1026 potential ET<sub>p</sub> was best for simulating ETs from 40 to 100 DAP (mostly canopy T) and  
1027 worse for -10 to +20 DAP (mostly soil E). The Priestly and Taylor (1972) method was best  
1028 for soil E and worse for canopy T. The ASCE Standardized Equation approach with short or  
1029 tall crop coefficients (Allen et al., 2005) was intermediate for canopy T and worst for soil E,  
1030 although this result might be somewhat biased because they were not independently  
1031 calibrated.

1032 4.7 DSSAT CSM-IXIM tended to be slightly better than DSSAT CSM-CERES for simulating  
1033 canopy T, probably because IXIM simulated leaf area progression better.

1034 4.8 Both STCK (which considers one surface to compute ET<sub>p</sub>) and STSW (which considers  
1035 both soil and canopy surfaces to compute ET<sub>p</sub>) were among the best models to simulate ETs  
1036 at the beginning of the seasons, with slightly better results for STSW. During the mid-  
1037 season periods, STCK globally performed better than STSW, but both performed poorly  
1038 with SDI in 2013, which distorted results.

1039 4.9 XNSM and XNGM appeared to do equally well at simulating both soil E and canopy T,  
1040 with XNGM following the more detailed Farquhar modeling approach in calculating  
1041 photosynthesis and leafT, but greatly simplifying vertical root distribution. However,

1042 XNSM did better than XNGM at simulating grain yield, possibly due to its simpler but more  
1043 robust approach in simulating assimilate distribution among plant organs.

1044 4.9 MZD and MZH both have hourly time steps, yet MZD which uses daily weather data did  
1045 slightly better than MZH which uses hourly weather data at simulating soil E, but there was  
1046 no significant difference between them at simulating canopy T. This is somewhat surprising,  
1047 but nevertheless shows that simulated diurnal patterns of hourly weather can be as accurate  
1048 as using the actual hourly observations for input to crop growth models with hourly time  
1049 steps.

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## **6 Supplementary information**

6.1 Word file with Table S1, which lists the ET simulation characteristics of the models plus several figures showing an intercomparison among the models in their ability to simulate soil moisture.

6.2 Excel file with statistics and graphs showing the Phase 4 performance of the models in their ability to simulate the daily ET observations for the irrigated and rainfed fields in Mead in 2003 and for the 100% and 75% MESA irrigated fields in Bushland in 2013. Also included

1074 are the statistics and graphs showing the models' ability to simulate cumulative ET from -10  
1075 to +20 DAP and from 41 to 100 DAP and agronomic parameters (maximum LAI, biomass at  
1076 about 100 DAP, and grain yields) for all 20 treatments.

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