Testing and Improving Evapotranspiration and Soil Water Balance of the DSSAT Crop Models

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ABSTRACT

Crop models have proven to be useful in establishing strategies to improve production under water-limiting conditions; however, this requires that models have accurate water balance. The objective of this paper was to evaluate various potential evapotranspiration (E0) equations and different ways of partitioning E0 between soil evaporation and crop transpiration within the DSSAT models and particularly the CROPGRO faba bean (*Vicia faba* L.) model. The default DSSAT E0 options of Priestley–Taylor (PT) and Penman-FAO (P-FAO24) as well as several equations based on Penman-Monteith theory, and an alternative E0 partitioning function were evaluated against measured time-series data on soil water content, actual evapotranspiration (ET), and crop biomass accumulation of faba bean grown under rainfed conditions in southwest Spain. We conclude (i) the PT option is reasonable but tends to overpredict ET, especially in early season, and its ET predictions are significantly improved when the extinction coefficient is reduced from its default value of 0.85 to 0.5; (ii) P-FAO24 is the least adequate to simulate ET and biomass; (iii) the Penman–Monteith reference method (PM-REF based on FAO no. 56 manual) gave good predictions for faba bean but tended to underpredict ET in other locations with soybean [*Glycine max* (L.) Merr.]; and (iv) dynamic forms of the Penman–Monteith option that use crop-model–predicted leaf area index and height effects on aerodynamic and surface resistance to water vapor transport also gave good predictions. For this crop and environment, ET prediction accuracy with all the ET options except the PM-REF was improved using a 0.5 extinction coefficient for net radiation.

WATER DEFICIT is a major limiting factor of crop production in the world. In many areas where precipitation is too low or inadequately distributed to cover the needs of crops, irrigation is seen as the principal means to intensify cropping systems. Nevertheless, with possible climate change taking place and human activities competing for water resources, agriculture has to search for cropping strategies to increase crop water use efficiency. In this context, one of the major problems in irrigated agriculture is to (i) establish when and how much water to apply at the field level and in rainfed agriculture and (ii) determine the best sowing date and optimum life cycle to take advantage of available soil water and precipitation. To address the first question (i) and rationalize water use in irrigated farming systems, the soil–crop water balance approach, with its estimation of ET from climatic data, has long been seen as an appealing technique due to the simplicity of the method when compared with on-site measurements (Blaney and Criddle, 1950; Doorenbos and Pruitt, 1975; Jagtap and Jones, 1989a; Itier and Brunet, 1996; Allen et al., 1998). Nevertheless, to be successful, the technique requires accurate ET estimation. Traditionally, the ET estimation of a crop requires calculating the E0, which has been defined as the maximum rate of water used by an extensive crop of full cover, including crop and soil, when water is not limiting. Thus, E0 defines the upper bound to ET and is mainly determined by the evaporative demand of the atmosphere. Penman (1948) proposed an equation to calculate E0 based on the rate of theoretical water loss from a free-water surface. At that time, differences in E0 between crops were not well documented, nor was it appreciated that E0 of many full-cover crops can reach values significantly larger than that of the short-grass standard (Loomis and Connor, 1992). Later, to minimize differences associated with canopy characteristics, researchers defined reference evapotranspiration (ETo; see list of abbreviations in Appendix) as the potential evapotranspiration of a short grass of well-defined characteristics (Doorenbos and Pruitt, 1975; Pereira et al., 1996; Allen et al., 1998). Since the publication of the FAO Irrigation and Drainage Paper no. 24 (Doorenbos and Pruitt, 1975), this concept was widely recommended and used as an intermediate step, with the crop coefficient (Kc) concept, to calculate ET of different crops under standard conditions (ETc = Kc × ETo; crop under optimum soil nutrient and water conditions) throughout the growing season. This method allows ETc to be larger than ETo. Thus, ETc redefines E0 because it considers effects of canopy characteristics of height, aerodynamic roughness, and maximum canopy conductance as described by Loomis and Connor (1992) and Villalobos et al. (2002). Many empirical or physically based equations have been proposed to estimate ETo: Blaney and Criddle (1950), Priestley and Taylor (1972), Hargreaves (1974), standardized Penman-FAO (described by Doorenbos and Pruitt, 1975), standardized Penman–Monteith (Allen et al., 1998), etc. Among the empirical and less weather-data–demanding equations, the Hargreaves (1974) formula that requires only maximum and minimum daily temperature as input proved to be the most reliable because the difference between maximum and minimum daily temperature provides an interesting way to derive solar radiation (SR) information for sites where these data are lacking (Itier and Brunet, 1996). The FAO and International Commission on Irrigation and Drainage working groups, after extensively trying different formulas among the physically based equations, recommended using the standardized Penman–Monteith

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instead of standardized Penman-FAO. The Penman-FAO equation, the earlier recommendation, was found to overestimate ETo under a large set of environments while the Penman–Monteith method has the advantage of including physiological and aerodynamic parameters (Allen et al., 1998).

To assist the second problem (ii), in the past, the only way to establish strategies to improve yield under a water-limiting environment was through long-term, multilocation field experiments (Loomis and Connor, 1992). However, during the last 15 yr, crop modeling has proven to be a powerful tool to extrapolate experimental data obtained under very specific weather and soil conditions to other cropping environments. This tool can shorten the experimental process needed to establish better cropping strategies using long-term, multiyear weather simulations and statistical analyses (Wilkerson et al., 1983; Parsh et al., 1991; Egli and Bruening, 1992; Singh et al., 1994; Jacobson et al., 1995; Boote et al., 1997; Ruíz-Nogueira et al., 2001). Nevertheless, the utility of crop models for this objective depends considerably on the accuracy of their water-balance modules.

Faba bean is an important winter grain legume crop in the Mediterranean Basin where it is generally grown under rainfed conditions (Saxena, 1985; FAO, 1999). It is considered one of the grain legumes better suited to produce high grain yields in these production systems (Siddique et al., 1993; Thomson and Siddique, 1997). Nevertheless, under this management, terminal water stress is almost unavoidable and is the prominent factor limiting yield. In addition, the water deficit level and timing in relation to the phenology of the crop have proven to be important (Grashoff, 1990a, 1990b; Mínguez et al., 1993; Sau and Mínguez, 2000).

The CROPGRO model was recently adapted to simulate faba bean growth and development processes (Boote et al., 2002). This model was shown to predict correctly the time course of the main ecophysiological growth parameters of N-fertilized and nonfertilized faba bean grown at Córdoba (southern Spain) under nonlimiting water conditions during two seasons. The faba bean option is included in the next DSSAT release (DSSAT V4.0; available from www.icasa.net/dssat/index.html; verified 28 June 2004).

The objectives of this paper were to evaluate effects of (i) various methods of E0 computation and (ii) different partitioning of ET between soil (evaporation) and crop (transpiration) components, upon the dynamics of ET, soil water content, and dry matter accumulation, as predicted by the CROPGRO model, for faba bean grown under different patterns of water availability at Córdoba (southern Spain). The CROPGRO faba bean model was previously calibrated for nonlimiting water conditions (Boote et al., 2002) and presently has two options for E0 computation [DSSAT V3.5 options: (i) Priestley–Taylor (Priestley and Taylor, 1972) and (ii) Penman-FAO (Jensen et al., 1990)]. As mentioned above, there have been recent advances in ET computations proposed by Allen et al. (1998), and it would be valuable to evaluate the possible benefits of including them as options in widely used simulation models included in the DSSAT. In addition, we wished to evaluate additional ET options based on the Penman–Monteith equation (Monteith, 1965, 1973) as well as different methods of partitioning of ET between soil (evaporation) and plant components (transpiration).

MATERIALS AND METHODS

Experimental Data

The experimental data used in this study came from the rainfed treatments of two field experiments sown on 10 Dec. 1986 (Exp. 1) and 24 Dec. 1987 (Exp. 2), on a deep alluvial, low-impedance soil (Typic Xerofluvent) at Córdoba in the Guadalquivir Valley, southern Spain (38°N, 4°W; 90 m elevation). In both cases, soil pH in water was 7.1, and the soil was fertilized before sowing according to analyses with ample amounts of P and K to remove any limitation of these two nutrients. A detailed description of the experiments and the weather variables during the two growing seasons can be found in Materials and Methods and Table 1 of Sau and Mínguez (2000).

The cultivar Alameda used in these studies is classified as *Vicia faba* L., indeterminate type of botanical variety major, and has an indeterminate growth pattern (Cubero, 1974). In Exp.1, plant density and row spacing were 19 plants m^{-2} and 0.7-m distance between rows; in Exp. 2, there were 26 plants m^{-2} and 0.35-m distance between rows. There were two treatments of N nutrition: (i) fertilized and not inoculated or (ii) not fertilized and inoculated. In the fertilized treatments, N was supplied through three applications of urea (sowing, beginning bloom, and end of bloom), with a total amount of 200 and 300 kg N ha^{-1} in Exp. 1 and 2, respectively. Treatments were replicated four times.

Dry weight of stems, petioles, leaves, and pods was measured and leaf area recorded at 15-d intervals based on 0.35 to 0.37 m^2 of sampled plant land area from each plot. A three-plant subsample was taken and separated into stems, petioles, leaves, flowers, and pods. All the subsample components and remaining plants were dried to constant weight in a convective oven at 70°C. Leaf area was estimated with a LI-COR planimeter Model LI-3000.

Soil water content measurements were made using a Campbell Pacific Model 503 neutron probe at intervals of 10 to 20 d throughout the growing season, starting at 61 and 49 d after sowing (9 February and 11 February) in 1987 and 1988, respectively. Access tubes were installed in the middle of the interrow of the center of each individual plot to a depth of 195 cm. Readings were taken at 30-cm intervals in the soil profile to a depth of 195 cm. The neutron probe was calibrated with gravimetric samples, and soil bulk density was accounted for. On the same days, soil samples were taken from the upper 15 cm, weighed, oven-dried for more than 48 h at 110°C, and weighed again to estimate water content. Soil water content data were the average of four replications. Root length density along the soil profile was measured three times in both experiments using a modified Newman method (Newman, 1966), as described by Álvarez de Toro (1987). The field capacity (drained upper limit) and permanent wilting point (lower limit) are shown in Table 1. Drained upper limit was estimated as the value occurring over time shortly after rainfall events or watering in the irrigated treatments while lower limit was estimated by the desiccation trend measured in the rainfed treatments at the end of the season. The saturated soil water content was estimated through measured values in similar soil profiles.

Measured Crop Evapotranspiration

To evaluate the accuracy of model estimation of ET, the calculation of measured ET between two neutron probe measurements was implemented, summing the precipitation of the period and the water content difference between the two measurement dates above a depth of 195 cm. Neutron probe measurements showed no evidence of drainage below 195-cm depth during these periods in the treatments of both experiments. As the experimental fields were level, subsurface water flow cannot be important. Under these conditions, the water budget approach based on actual measurements of soil water using neutron scattering is accepted as an adequate method to estimate total ET from a 0.35- or 0.70-m row crop due to its relatively large operational range (more than 0.25 m in a medium-textured unsaturated soil) (Dane and Topp, 2002).

CROPGRO Model: Soil Water Balance and Evapotranspiration Options

The model used in this paper is the mechanistic process-level CROPGRO model (Boote et al., 1998; DSSAT V3.5 release), obtained after modifications of the species file and the definition of the cultivar's genetic and ecotype coefficients (Boote et al., 2002) that allowed satisfactory prediction of faba bean crop development and growth under nonlimiting water conditions. The daily soil water balance and rooting of CROPGRO are described below, along with the two default ET options available and several alternative ET equations related to the Penman–Monteith ET combination model theory (Penman, 1948; Monteith, 1965, 1973) and a modification for partitioning ET between evaporation and transpiration.

Soil Water Balance, Root Growth, and Water Uptake in CROPGRO

The daily soil water balance in the CROPGRO model, as in all the DSSAT 3.5 models, uses the Ritchie (1985) one-dimensional "tipping bucket" soil water balance approach, which predicts soil water flow and root water uptake for each of up to 10 soil layers. Using this method requires each layer of the soil profile to be defined, in the SOIL.SOL file, by a characteristic drained upper limit, a lower limit, a saturated soil water content, and a soil rooting preference function [WR(L)] that quantifies the potential root hospitality of the layer. Actual root length density depends on: (i) crop model allocation of dry matter to roots, (ii) rate of root depth progression, (iii) WR(L), and (iv) the soil water content in each zone. Roots tend to grow faster into moist soil layers than in dry or saturated layers. The WR(L) for these experiments was previously calibrated by Boote et al. (2002) (Table 1), and the simulations of the root length density over time in the different layers of the soil profile were able to mimic satisfactorily those experimentally measured by Sau and Mínguez (2000). Root potential water uptake from each soil layer is computed as a function of water content and root length density in each layer. The potential root water uptake of the crop (RWU) is computed as the sum of the root potential water uptake from all the soil layers.

Partitioning to Evaporation and Transpiration in CROPGRO

The DSSAT models compute E0 for each specific crop, which may include leaf area index (LAI) and canopy architecture effects as Kc approach and dynamic ET options become available. Then the models partition E0 to potential soil evaporation (ES0) and potential plant transpiration (EP0), following the Ritchie (1972, 1985) approach, which considers the portion of SR reaching the soil that can be spent as latent energy to evaporate water from the soil surface if the soil is wet (Eq. [1] and [2]). The fraction of SR reaching the soil is a function of LAI. Actual soil evaporation (ES) and plant transpiration (EP) subsequently depend on the availability of water to meet these potential rates (Eq. [3] to [4]).

Table 1. Principal characteristics of the different layers of the experimental soil profile (Exp. 1 and 2).

Soil layer	LL†	DUL‡	SAT§	Soil rooting preference function (0.00–1.00)¶
cm	% vol.			
		Exp. 1		
0–15	7.0	27.0	39.0	1.00
15–45	7.0	25.0	35.0	0.61
45–75	7.0	22.0	32.0	0.42
75–105	7.0	20.0	30.0	0.32
105–135	7.0	19.5	28.5	0.20
135–165	7.0	18.0	28.0	0.11
165–195	7.0	22.0	31.0	0.06
		Exp. 2		
0–15	9.0	36.5	47.0	1.00
15–45	11.5	30.0	41.0	0.61
45–75	11.5	29.0	40.0	0.42
75–105	11.5	27.0	36.0	0.32
105–135	11.5	25.0	35.0	0.20
135–165	11.5	23.5	34.0	0.11
165–195	11.5	23.5	35.0	0.06

† LL, lower limit or wilting point.
‡ DUL, drained soil water upper limit.
§ SAT, soil water upper limit or saturated soil water content.
¶ Soil rooting preference function used by the CROPGRO model.

The ES0 in DSSAT V3.5 is calculated from E0 as follows, using the equations taken from Jones and Kiniry (1986):

$$\text{IF LAI} < 1.0 \text{ THEN ES0} = \text{E0} \times (1.0 - 0.43 \times \text{LAI}) \quad [1]$$

$$\text{IF LAI} > = 1.0 \text{ THEN ES0} = \text{E0}/1.1 \times \exp(-0.4 \times \text{LAI}) \quad [2]$$

The DSSAT 3.5 models follow the premise (Ritchie, 1985) that ES takes place in two stages: (i) the constant stage or energy limited (Stage 1) and (ii) the falling-rate stage (Stage 2). During Stage 2, ES is smaller than ES0. Partitioning of E0 to climatic EP0 is calculated using Eq. [3] and [4], with an extinction coefficient of 0.85 for CROPGRO models (although the CERES-maize model in DSSAT V3.5 uses an extinction value of 1.0 up to LAI of 3.0, with an IF condition that allows EP0 to be equal to E0 when LAI exceeds 3.0) (Ritchie, 1972, 1998; Jones and Kiniry, 1986).

$$\text{EP0} = \text{E0} \times [1.0 - \exp(-0.85 \times \text{LAI})] \quad [3]$$

$$\text{IF EP0} + \text{ES} > \text{E0 THEN EP0} = \text{E0} - \text{ES} \quad [4]$$

Literature review shows a range of previously measured values for the extinction coefficient (K) for partitioning of E0 to EP0: 0.44 for corn (*Zea mays* L.) (Childs et al., 1977), 0.52 for corn and cotton (*Gossypium hirsutum* L.) (Villalobos and Fereres, 1990), 0.79 for cowpea [*Vigna unguiculata* (L.) Walp.] (Sepaskhah and Ilampour, 1995), and from 0.54 to 0.63 for wheat (*Triticum aestivum* L.) and corn (Kang et al., 2003). In addition, the model of Belmans et al. (1983) uses 0.60 for crops in general. From these values, we could hypothesize that an extinction coefficient of 0.85 for partitioning E0 to EP0 is too high.

In addition, the use of extinction partitioning coefficient of

0.5 for total solar irradiance is supported by theory. Assuming that 47% of SR is photosynthetically active radiation (PAR) and the rest (53%) is primarily near-infrared radiation (NIR), and that the leaf scattering coefficient (σ) is 0.2 and 0.8 for PAR and NIR, we can derive weighted apparent extinction coefficients for SR through the following equation: $K = K_{bl} \times (1 - \sigma)^{0.5}$ (Goudriaan, 1977; Goudriaan and van Laar, 1994), where K_{bl} is the leaf extinction coefficient for radiation if the leaf is opaque (black). Considering values for K_{bl} between 0.7 and 0.8, the derived weighted extinction coefficient for total solar would be between 0.46 and 0.53. Weighted K equals $0.47 \times [K_{bl} \times (1 - 0.20)^{0.5}] + 0.53 \times [K_{bl} \times (1 - 0.80)^{0.5}]$. Lastly, Flénet et al. (1996) have measured for soybean with 0.35- and 0.66-m row spacing an average daily extinction coefficient for PAR of 0.592. Using this value and the Goudriaan (1977) equation, we can derive a K_{bl} of 0.66 and a weighted K for SR of 0.44 and that a value close to 0.5 may be more adequate. This result also confirms that an extinction coefficient for SR of 0.85 is too high.

Finally, the transpiration of the crop (EP) is computed through Eq. [5] and [6], and the water deficit factors on photosynthesis (SWFAC) and turgor (TURFAC) are calculated in Eq. [7] and [8], respectively. SWFAC and TURFAC reduce, in direct proportion, potential dry matter growth and LAI expansion of the day, respectively, as these stress factors change from 1 (no water stress) to 0 (maximum stress or no transpiration water loss). The 1.5 factor in Eq. [8] allows the simulated expansion processes to respond earlier to water deficit than dry matter growth.

$$\text{IF RWU} \geq \text{EP0 THEN EP} = \text{EP0} \qquad [5]$$

$$\text{IF RWU} < \text{EP0 THEN EP} = \text{RWU} \qquad [6]$$

$$\text{SWFAC} = \text{EP/EP0} \qquad [7]$$

$$\text{TURFAC} = \text{EP}/(1.5 \times \text{EP0}) \qquad [8]$$

Equations [1] to [4] show that the DSSAT models dynamically partition E0 between ES and EP using model-simulated LAI effects on EP0 and ES0 as well as effects of dynamically changing soil water content of the upper evaporating soil layers. By contrast, stand-alone methods lacking LAI, such as used in FAO no. 56 manual (Allen et al., 1998), first compute the ETo and then calculate ETc, using a dual-coefficient approach [ETc = (Ke + Kcb) × ETo, where Ke is the soil evaporation coefficient and Kcb is the basal crop coefficient] that allows ETc to be larger than ETo. At a given growth stage, Ke decreases as the soil dries while Kcb defines the soil and crop minimum water loss when the soil is dry and follows a fixed four-point function based on crop life stages.

Priestley–Taylor Modified by Ritchie Potential Evapotranspiration Option

In the DSSAT 3.5 default water balance, E0 is estimated using a functional model, formulated by Ritchie (1972, 1985), where E0 is calculated using the equilibrium evapotranspiration (EEQ) in the same way proposed by Priestley and Taylor (1972) (Eq. [9]), but EEQ is calculated through simplified Ritchie equations (Eq. [10]).

$$\text{E0} = \alpha \times \text{EEQ} \qquad [9]$$

$$\text{EEQ} = \text{SR} \times 2.04 \times 10^{-4} - 1.83 \times 10^{-4} \times \text{ALBEDO} \times (0.60 \times \text{Tmax} + 0.4 \times \text{Tmin} + 29.0) \qquad [10]$$

where α is a coefficient of advectivity, SR is daily total solar radiation in MJ m^{-2} d^{-1}, ALBEDO is the crop albedo, and Tmax (°C) and Tmin (°C) are daily maximum and minimum temperatures, respectively. In Eq. [9], EEQ is expressed in MJ m^{-2} d^{-1} and needs to be multiplied by 0.408 to be converted to mm d^{-1}.

The literature shows that α can vary from 1.08 to more than 1.60 as a function of the advectivity of the environment (Villalobos et al., 2002). In the DSSAT V3.5 models, α is set as 1.1 when temperature is between 5 and 35°C. Below 5°C and above 35°, computed α is slightly smaller or larger than 1.1, respectively. This ET method will be called the Priestley–Taylor option or PT (1). This option assumes that all crops have the same E0.

Penman-FAO Potential Evapotranspiration Option

If daily wind speed average and dew point temperature are provided, DSSAT V3.5 also allows E0 to be calculated through a second method, the Penman-FAO Option (2), or P-FAO24 (Eq. [11]), as it was described and recommended in the FAO Irrigation and Drainage Paper no. 24 (Doorenbos and Pruitt, 1975; Jensen et al., 1990). Like the PT option, this option does not consider any Kc and assumes that all crops have the same E0.

$$\text{E0} = [(\Delta \times \text{Tmax} + \Delta \times \text{Tmin})/2 \times \text{Rn} + Y \times (0.0027 \times 1.0 + 0.01) \times U_2 \times \text{VPD}]/[(\Delta \times \text{Tmax} + \Delta \times \text{Tmin})/2 + Y] \qquad [11]$$

where Δ (Pa K^{-1}) represents the slope of the saturation vapor pressure, Rn (mm d^{-1}) is the net radiation, Y (Pa K^{-1}) is the psychrometric constant, VPD (Pa) is vapor pressure deficit, U_2 (km d^{-1}) is wind speed at 2-m height, and Tmax and Tmin are in °C.

Alternative Potential Evapotranspiration Options: Penman–Monteith

The Penman–Monteith Eq. [12] has been used in many forms, including fixed reference crop formats that fix LAI, crop height, stomatal resistance, or dynamic forms that make the use of changes in LAI, crop height, or stomatal resistance and different time steps as hour or day. All use wind speed and VPD in the primary calculation.

$$\text{E0 (MJ m}^{-2}\text{ d}^{-1}) = [\Delta \times (\text{Rn} - G) + \rho\text{a} \times \text{Cp} \times \text{VPD/Ra}]/[\Delta + Y \times (1 + \text{Rs/Ra})] \qquad [12]$$

where Δ and Y are in kPa °C^{-1}, Rn in MJ m^{-2} d^{-1}, VPD in kPa, G (MJ m^{-2} d^{-1}) is the soil heat flux density (can be ignored when E0 is calculated on a daily basis), ρa (kg m^{-3}) is the mean air density at constant pressure, Cp (MJ kg °C^{-1}) is the specific heat of the air at constant pressure, Ra (s m^{-1}) is the aerodynamic resistance of the canopy, and Rs (s m^{-1}) is the "bulk" surface resistance of water vapor flow through the transpiring crop and evaporating soil surface.

Penman–Monteith Reference Method

Most commonly, the Penman–Monteith Eq. [12] has been reduced to the reference crop form, for a theoretical grass of 0.12-m height, surface resistance of 70 s m^{-1} (based on assumption of LAI = 2.88 and a fixed leaf resistance of 100 s m^{-1}), a fixed ALBEDO, and the wind speed defined at 2.0-m height, as described by Allen et al. (1998). In this form, the computed aerodynamic resistance is well behaved, being only a function of wind speed. The equation form we named PM-

REF (3) uses these constants and was computed as described by Allen et al. (1998) following this simplified form:

$$\text{E0 (mm d}^{-1}) = \{0.408 \times \Delta \times (\text{Rn} - G) + [Y \times 900/(\text{Tavg} + 273)] \times U_2 \times \text{VPD}]\}/[\Delta + Y \times (1 + 0.34 \times U_2)] \quad [13]$$

where Tavg and U_2 are mean daily temperature (°C) and wind speed (m s^{-1}) measured at 2-m height, respectively. The other variables and units are as defined for Eq. [12]. In fact, Eq. [12] gives the same results if wind, LAI, and height effects on Rs and Ra are input. This option does not consider any Kc and assumes that all crops have the same E0.

In addition, we tried another option (PM-REF-Kc) where the reference form [13] is multiplied by a crop coefficient (Kc) that increases E0 as a function of LAI to obtain the ETc concept, as done in the CROPSYST model [www.bsyse.wsu.edu/cropsyst/; verified 13 June 2004; Stockle and Nelson, 1996; note: this method is not described by Allen et al. (1998) in the FAO no. 56 manual], and Kc = (1.0 + 0.X × LAI/LAImax) [14] is defined between LAI of 0 to 6. This form defines E0 of bare wet soil (with zero LAI) to be the same as the E0 of the reference grass crop (ETo; 0.12 m tall and LAI of 2.88). In the crop model, the model supplies the varying LAI relative to LAImax (theoretical maximum LAI of 6.0), and ETc can reach a maximum of 1.X × ETo. Allen et al. (1998) showed for faba bean that maximum Kc can vary between 1.0 and 1.3, as a function of the crop and the environment. In this work, we tried two PM-REF-Kc suboptions where 1.X is equal to 1.1 (PM-REF-1.1) (4) and 1.2 (PM-REF-1.2) (5), respectively. In these options, LAI is calculated daily by the crop model and then used to compute Kc. In addition, Options (4) and (5) will help to establish the best Kc coefficient for faba bean under this Mediterranean environment.

Dynamic Penman–Monteith Potential Evapotranspiration Methods that Use Varying Crop Height and Leaf Area Index

We also tried two dynamic equation forms (PM-D) that use calculation of Ra as a dynamic function of crop height and calculation of Rs as dynamic function of changing LAI (and possible changes in the resistance of single leaves associated with environment). Leaf area index and crop height are calculated daily by the crop model and then used for E0 (E0 = ETc) computation. In our paper, we attempted two methods for computing Ra.

Steiner et al. (1991) and Allen et al. (1998) use the same form of the equation for Ra (Eq. [16]), but Steiner et al. used a somewhat different d (zero-plane displacement height in meters) (Eq. [17] instead of [21]) and Zom (roughness length governing momentum transfer in meters) (Eq. [18] instead of [22]). Most importantly, Steiner et al. (1991) clearly articulated that Zr is not 2.0 m absolute height but is the reference height for wind speed in meters relative to the crop, thus Zr = 2.0 + H (H is crop height in meters) (Eq. [15]). Steiner et al. provided Eq. [20] for adjusting wind speed at 2.0-m height over grass (assumed 0.12 m) to the wind speed at 2.0 m over any crop. Manual recomputation of Ra values reported by Kjelgaard and Stockle (2001) confirm the appropriate use of Zr = 2.0 + H for computation of Ra.

$$\text{Ra} = \{\ln[(\text{Zr} - \text{d})/\text{Zom}] \times \ln[(\text{Zr} - \text{d})/\text{Zoh}]\}/[(k^2) \times U_{2s}] \quad [16]$$

where

$$\text{d} = 0.75 \times H \quad [17]$$

$$\text{Zom} = 0.25 \times (H - \text{d}) \quad [18]$$

$$\text{Zoh} = 0.1 \times \text{Zom} \quad [19]$$

where Zoh is the roughness length governing heat and water vapor (m).

$$U_{2s} = U_{2g} \times \{\ln[(10 - 0.075)/0.00625] \times \ln[(2 + H - \text{d})/\text{Zom}]\}/\{\ln[(10 - \text{d})/\text{Zom}] \times \ln[(2 - 0.075)/0.00625]\} \quad [20]$$

where

U_{2g} = wind speed (s m^{-1}) at 2 m over grass
U_{2s} = wind speed at 2 m above the crop, at Zr
10 = arbitrary height (m) at which wind speed is considered not to be affected by crop
d = 0.075 m, for grass that is 0.10 m tall
Zom = 0.00625 m, for grass

The Ra of Eq. [16] above, from Allen et al. (1998; FAO Irrigation and Drainage Paper no. 56), is the same as that from Steiner et al. (1991), but some of the variables are calculated differently (Eq. [21] and [22]), leading to lower Ra values (71–72% of Steiner et al.) and as a result causing higher E0.

$$\text{d} = 0.667 \times H \quad [21]$$

$$\text{Zom} = 0.123 \times H \quad [22]$$

With the PM-D options, we used the approach proposed by Allen et al. (1998) to calculate Rs:

$$\text{Rs} = \text{Rl}/(0.5 \times \text{LAI}) \quad [23]$$

where half of the LAI was considered active and Rl is the single leaf resistance considered constant at 100 s m^{-1}.

The dynamic formulations of Penman–Monteith following Allen et al. (1998) and Steiner et al. (1991) for Ra computation are referred to as PM-D-FAO56 (6) and PM-D-ST (7) methods, respectively. Implementations of the Penman–Monteith equations sometimes appear to ignore the soil evaporation resistance term or bare-soil Ra (Ra-soil; aerodynamic resistance of bare soil to water vapor transport) although the Rs term actually includes soil evaporation. “Surface resistance term in the Penman–Monteith equation represents the resistance to vapor flow from within plant leaves and from beneath the soil surface” (Allen et al., 1998, p. 90). Therefore, we added a term for surface resistance of bare soil to water transport (Rs-soil) to the dynamic Penman–Monteith forms, as well as the term Ra-soil, and appropriately weighted each according to crop cover (AC) to calculate potential ET but adjusted to give reference ET at zero LAI. The Rs-soil term was based on Eq. [28] proposed by Jagtap and Jones (1989b).

$$\text{Rs-soil} = \ln(\text{Zr}/\text{Zos}) \times \ln[(\text{d} + \text{Zoc})/\text{Zos})]/[(k^2) \times U_{2g}] \quad [24]$$

where Zr = 2.0 m and Zos = 0.03 m

$$\text{d} + \text{Zoc} = 0.85 \times \text{Hs} \quad [25]$$

where Hs = 1.0 m (arbitrary “height of soil”).

Soil roughness (Zos) was set to 0.03 m to ensure that the intercept to zero LAI gives ET comparable to reference ET when computed in the fraction crop cover approach outlined below. This procedure works because the crop–soil model limits actual ES of bare soil as the soil dries.

Finally, Ra-soil was calculated, using the standard FAO equation for Ra, with input of "effective height" of soil of 0.25 m. For bare soil, the Zr was always 2.0 m, and wind speed corresponded to 2.0-m height.

Weighted Ra or Rs were computed before being used in the different PM-D equations. They were weighted for fraction crop cover as a function of LAI, as follows:

$$AC = [1 - \exp(-0.5 \times LAI)] \quad [26]$$

$$\text{Rs-total} = AC \times \text{Rs-crop} + (1 - AC) \times \text{Rs-soil} \quad [27]$$

$$\text{Ra-total} = AC \times \text{Ra-crop} + (1 - AC) \times \text{Ra-soil} \quad [28]$$

where AC is a weighting or partitioning factor, Rs-total is surface resistance to water vapor transport of the soil and crop (s m^{-1}), Rs-crop is surface resistance to water vapor transport of the crop (s m^{-1}), and Ra-crop is aerodynamic resistance to water vapor transport of the crop (s m^{-1}). Practically speaking, the AC weighting factors make the transition from 100% bare soil (with its own Ra and Rs) to almost 100% crop dominated (Ra and Rs coming predominantly from crop). Weighting and partitioning approaches used in this paper as a function of LAI extinction of net radiation have previously been used by Lhomme and Monteny (2000) and by Sellers et al. (1996).

Partitioning of Potential Evapotranspiration to Soil Potential Evaporation and Crop Potential Transpiration

Finally, we attempted to use the same extinction coefficient of $K = 0.5$ for canopy absorption of net radiation, for net radiation reaching the soil surface, for the partitioning of E0 to crop vs. soil, for the weighting of Rs-soil and Rs-crop, and for weighting of Ra-soil and Ra-crop for the PM-D equations. The K value of 0.5 is defendable from theory of weighted average of the absorption coefficients for PAR and NIR for spherical leaf angle distributions (Goudriaan and van Laar, 1994; Lhomme and Monteny, 2000). Values of 0.52 were obtained in experimental observations of evaporation and transpiration components of ET of corn, sunflower (*Helianthus annuus* L.), and cotton (Villalobos and Fereres, 1990). We concluded that it may not be correct to assume that extinction coefficients for total SR can be taken directly from those used for PAR. The original coefficients derive from Ritchie (1972), with $K = 1.0$ for CERES-Maize, and later decreased to $K = 0.85$ for CROPGRO. Furthermore, the effective K values are lower when canopies are sparse, which is the time when LAI is relatively low and weighting effects and partitioning of energy are more important.

So we substituted the original equations, [1] and [2] by [29] and [3] by [30], respectively.

$$ES0 = E0 \times \exp(-0.5 \times LAI) \quad [29]$$

$$EP0 = E0 \times [1 - \exp(-0.5 \times LAI)] \quad [30]$$

The use of the $K = 0.5$ for the partitioning of E0 to canopy vs. soil created a new complete suite of minor ET options (8–14). These are named following the system described previously and adding -.5 to indicate that the extinction coefficient used in Eq. [26], [29], and [30] is 0.5, i.e., PT-.5 (13).

In summary, we tried seven different options to calculate E0. One group of ET options used the original K values to partition E0 to E0S and EP0 in Options (1) to (7). A second group of ET options used uniform K of 0.5 in Options (8) to (14). All other relationships and methods for computing processes in the soil water balance remained unchanged.

Statistical and Graphical Procedures to Evaluate the Different Evapotranspiration Options

The following criteria were used to assess the different submodel performances: (i) intercept (a) and slope (b) values of linear regression between predicted and observed accumulated crop ET since the first neutron probe measurement date [day of year (DOY) 40, 65, 75, 92, 110, 124, and 138 in 1987 and DOY 42, 61, 71, 88, 109, 138, and 151 in 1988] and total aboveground biomass at the two last sampling dates before harvest (DOY 114 and 128 in 1987 and 130 and 143 in 1988), (ii) the root mean square error of these variables (RMSE), and (iii) an index of agreement (d; Willmott, 1982). Finally, predicted time series graphs of crop ET, total soil water content, and biomass were also compared visually with measurements to assess performance of the different ET options.

For testing prediction of simulated ET vs. observed ET, we consider that the RMSE is the most valuable statistic, with lower RMSE being desirable. The intercept (a) and slope (b) values are also important because high intercept (a) means the model overpredicted ET during early season. Intercept values closer to zero are desirable. Slopes (b) close to 1.0 indicate better predictions. Lastly, the index of agreement, d, is an aggregate overall indicator that is of more value than R^2.

To test if the RMSEs obtained for different ET options were significantly different, estimation of the RMSE variance for the models was computed through the bootstrapping technique (Efron and Tibshirani, 1986; Sprent, 1992) using 4000 resampling groups with replacement from the empirical data. Root mean square error estimators were found to be approximately normally distributed after performing appropriate tests using the PROC UNIVARIATE from SAS (SAS Inst., 2000). As the RMSE estimators among the models proved to be correlated, a variance–covariance matrix for the RMSE estimators was generated from the bootstrapping sampling technique to test (Student t test, 23 df) whether the RMSE difference between two ET options (models) was significantly different. Two ET options were considered significantly ($p < 0.01$) different when:

$$RMSE_i - RMSE_j > t_{0.01,23} (\sigma^2_{RMSE_i} + \sigma^2_{RMSE_j} - 2\sigma_{RMSE_i,RMSE_j})^{1/2}$$

where $RMSE_i$ and $RMSE_j$ are the RMSE estimators of options i and j, respectively; $t_{0.01,23}$ is the tabular two-tails t value at 0.01 level of probability and 23 degrees of freedom since the empirical data had 24 independent observations; $\sigma^2_{RMSE_i}$ and $\sigma^2_{RMSE_j}$ are the variances of RMSE estimators for options i and j, respectively; and $\sigma_{RMSE_i,RMSE_j}$ is the covariance between the RMSE estimators of options i and j. The statistics were done including all treatments while graphs present only the unfertilized, inoculated treatment. These treatments had no effects on ET or water extraction.

RESULTS AND DISCUSSION

To evaluate the various ET options, we looked at time series graphs of soil water content, ET, and dry matter accumulation. Statistics of 1:1 comparisons were also computed (Tables 2, 3, and 4). These three types of variables should show consistency between each other in prediction because the remaining soil water content in the various layers depends on the cumulative ET and dry matter accumulation late in the drought cycle depends on continued soil water supply and continued ET. For example, Fig. 1 and 2 illustrate the simulated soil

Table 2. Statistical estimators of the accuracy of the prediction of the measured time series evapotranspiration (ET) of the rainfed treatments with different ET options in Exp. 1 and 2: *a* and *b* values of linear regression of predicted vs. observed data, root mean square error (RMSE), estimated RMSE variance through the bootstrapping method (in parentheses), and index of agreement *d* (Willmott, 1982).

ET options	no.†	*a*	*b*	RMSE	*d*
PT	1	18.739	1.005	23.28 (5.23)	0.986
P-FAO24	2	20.873	1.049	32.37 (8.35)	0.975
PM-REF	3	10.952	0.976	13.58 (3.32)	0.995
PM-REF-1.1	4	10.036	1.016	16.70 (4.55)	0.993
PM-REF-1.2	5	10.092	1.046	21.01 (5.36)	0.989
PM-D-FAO56	6	6.697	1.068	21.69 (5.87)	0.989
PM-D-ST	7	5.147	1.059	18.67 (5.35)	0.992
PT-.5	8	11.289	0.996	18.74 (5.62)	0.991
P-FAO24-.5	9	11.860	1.054	26.22 (8.99)	0.984
PM-REF-.5	10	5.782	0.964	13.71 (1.85)	0.995
PM-REF-1.1-.5	11	4.944	1.002	14.16 (3.56)	0.995
PM-REF-1.2-.5	12	4.051	1.038	16.58 (5.03)	0.993
PM-D-FAO56-.5	13	0.660	1.073	18.92 (6.45)	0.992
PM-D-ST-.5	14	0.537	1.047	15.09 (4.52)	0.994

† 1 = Priestley–Taylor; 2 = Penman following Doorenbos and Pruitt (1975); 3 = Penman–Monteith Reference following Allen et al. (1998); 4 and 5 = Penman–Monteith Reference with a maximum crop coefficient of 1.1 and 1.2, respectively; 6 and 7 = Penman-Monteith Dynamic with two different approaches to compute aerodynamic resistance [FAO56 (Allen et al., 1998) and ST (Steiner et al., 1991), respectively]. Options 8–14 correspond to the previous description but using a uniform extinction coefficient of 0.5.

Table 4. Statistical estimators of the accuracy of the prediction of the two biomass sampling dates before harvest of the rainfed treatments with different evapotranspiration (ET) options in Exp. 1 and 2: *a* and *b* values of linear regression between predicted vs. observed data, root mean square error (RMSE), and index of agreement *d* (Willmott, 1982).

ET options	no.†	*a*	*b*	RMSE	*d*
PT	1	3581	0.534	1599	0.843
P-FAO24	2	4372	0.372	2412	0.622
PM-REF	3	3161	0.620	1272	0.908
PM-REF-1.1	4	3272	0.585	1399	0.885
PM-REF-1.2	5	3565	0.523	1692	0.825
PM-D-FAO56	6	3814	0.455	2094	0.728
PM-D-ST	7	3338	0.552	1602	0.847
PT-.5	8	3348	0.587	1362	0.891
P-FAO24-.5	9	3635	0.500	1835	0.793
PM-REF-.5	10	3063	0.640	1235	0.915
PM-REF-1.1-.5	11	3255	0.602	1322	0.899
PM-REF-1.2-.5	12	3317	0.573	1456	0.875
PM-D-FAO56-.5	13	3512	0.520	1746	0.815
PM-D-ST-.5	14	3266	0.576	1463	0.874

† 1 = Priestley–Taylor; 2 = Penman following Doorenbos and Pruitt (1975); 3 = Penman–Monteith Reference following Allen et al. (1998); 4 and 5 = Penman–Monteith Reference with a maximum crop coefficient of 1.1 and 1.2, respectively; 6 and 7 = Penman–Monteith Dynamic with two different approaches to compute aerodynamic resistance [FAO56 (Allen et al., 1998) and ST (Steiner et al., 1991), respectively]. Options 8–14 correspond to the previous description but using a uniform extinction coefficient of 0.5.

water content of respective layers as the season progresses in both Exp. 1 and Exp. 2 for two of the poorer ET options [PT (1) and P-FAO24 (2)] compared with two of the better ET options [PM-REF-.5 (10) and PM-D-ST-.5 (14)]. From Fig. 1 and 2, we can see the generally good predictions of soil water content in the different layers over time but also that the P-FAO24 version (and the PT version as well) generally predicts too much extraction, especially early in spite of a correct early-season LAI simulation (Fig. 3). This phenomenon of too low simulated soil water contents for the PT-FAO24 and the PT method is also reflected in the overestimated simulated ET of these ET options in both years (Fig. 4), whereas the other ET options give better predictions. The DSSAT model defaults (PT or the P-FAO24 options) especially predict too much water extraction early in the season (shallower soil depths), which we will subsequently point out is caused by their relatively high extinction coefficient ($K = 0.85$) for partitioning E0 to EP0. Symptoms of overprediction of ET during early season (Fig. 4) for the poorer ET options with original K values are reflected in higher intercepts (a) and higher RMSE values (Table 2). In addition, in Table 3, we will note whether differences in RMSE between ET options are statistically significant. Lastly, we will see that ET options that either predict too much water extraction during early season or generally have too high ET prediction run out of water sooner and cease dry matter accumulation sooner than the actual crop (see Fig. 5). The continuation of dry matter accumulation during late season is a third and more independent test that can show when certain ET options fail to work properly as shown by statistics for biomass prediction in Table 4.

Table 3. Statistical comparison of evapotranspiration (ET) options against each other based on differences of root mean square errors (RMSEs), computed using the bootstrapping method.

ET options no.†	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	–	s‡	s	s	ns	ns	s	s	ns	s	s	s	s	s
2	s	–	s	s	s	s	s	s	s	s	s	s	s	s
3	s	s	–	s	s	s	s	s	s	ns	ns	ns	s	ns
4	s	s	s	–	s	s	ns	s	s	ns	s	ns	ns	ns
5	ns	s	s	s	–	ns	s	ns	s	s	s	s	ns	s
6	ns	s	s	s	ns	–	s	ns	s	s	s	s	ns	s
7	s	s	s	ns	s	s	–	ns	s	ns	s	ns	ns	s
8	s	s	s	s	ns	ns	ns	–	s	ns	s	ns	ns	s
9	ns	s	s	s	s	s	s	s	–	s	s	s	s	s
10	s	s	ns	ns	s	s	ns	ns	s	–	ns	ns	ns	ns
11	s	s	ns	s	s	s	s	s	s	ns	–	s	s	ns
12	s	s	ns	ns	s	s	ns	ns	s	ns	s	–	s	s
13	s	s	s	ns	ns	ns	ns	ns	s	ns	s	s	–	s
14	s	s	ns	ns	s	s	s	s	s	ns	ns	s	s	–

† 1 = Priestley–Taylor; 2 = Penman following Doorembos and Pruitt (1975); 3 = Penman–Monteith Reference following Allen et al. (1998); 4 and 5 = Penman–Monteith Reference with a maximum crop coefficient of 1.1 and 1.2, respectively; 6 and 7 = Penman–Monteith Dynamic with two different approaches to compute aerodynamic resistance [FAO56 (Allen et al., 1998) and ST (Steiner et al., 1991), respectively]. Options 8–14 correspond to the previous description but using a uniform extinction coefficient of 0.5.

‡ "s" indicates RMSEs corresponding to two different ET options are significantly different at 0.01 level.

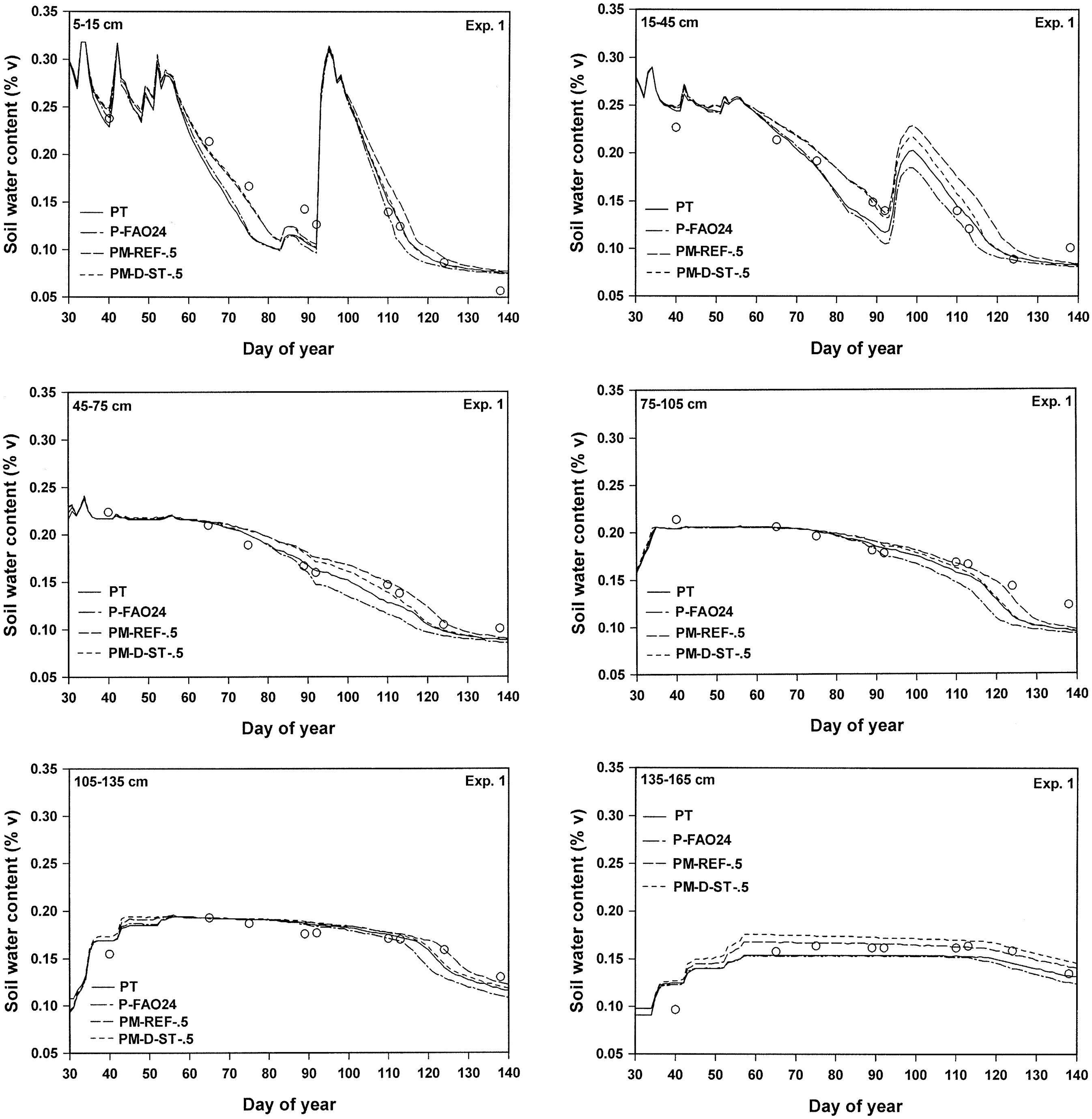


Fig. 1. Observed (points) and simulated (lines) dynamics of the soil water content (SWC) of the different soil layers during Exp. 1 rainfed season, using CROPGRO-faba bean and four evapotranspiration options: PT (1), Priestley–Taylor (Priestley and Taylor, 1972); P-FAO24 (2), modified Penman (Doorenbos and Pruitt, 1974); PM-REF-.5 (10), Penman–Monteith for the reference crop (Allen et al., 1998) with an extinction coefficient of 0.5; and PM-D-ST -.5 (14), Penman–Monteith dynamic with the bulk surface resistance calculated from leaf area index and aerodynamic resistance of the canopy calculated according to Steiner et al. (1991) and an extinction coefficient of 0.5.

Predicted Crop Evapotranspiration and Soil Water Content over Time: Priestley–Taylor (1) or Penman-FAO (2) Options

We will next discuss the behavior of various specific individual ET options in predicting ET and late-season dry matter accumulation. We especially wanted to test the PT option and the P-FAO24 option as the PT is the default in the DSSAT models. The P-FAO24 is also an option in the DSSAT models if wind and humidity data are available. As the DSSAT suite of models have been used worldwide since the 1980s, and partly because the PT option is less weather data demanding of ET methods, the PT method has been employed many times [e.g., to search for better rainfed management strategies (Ruíz-Nogueira et al., 2001) or to predict the effect of climate change on yield (Guerena et al., 2001)]. Our null hypothesis, therefore, is that the PT option as configured in DSSAT adequately predicts the time course

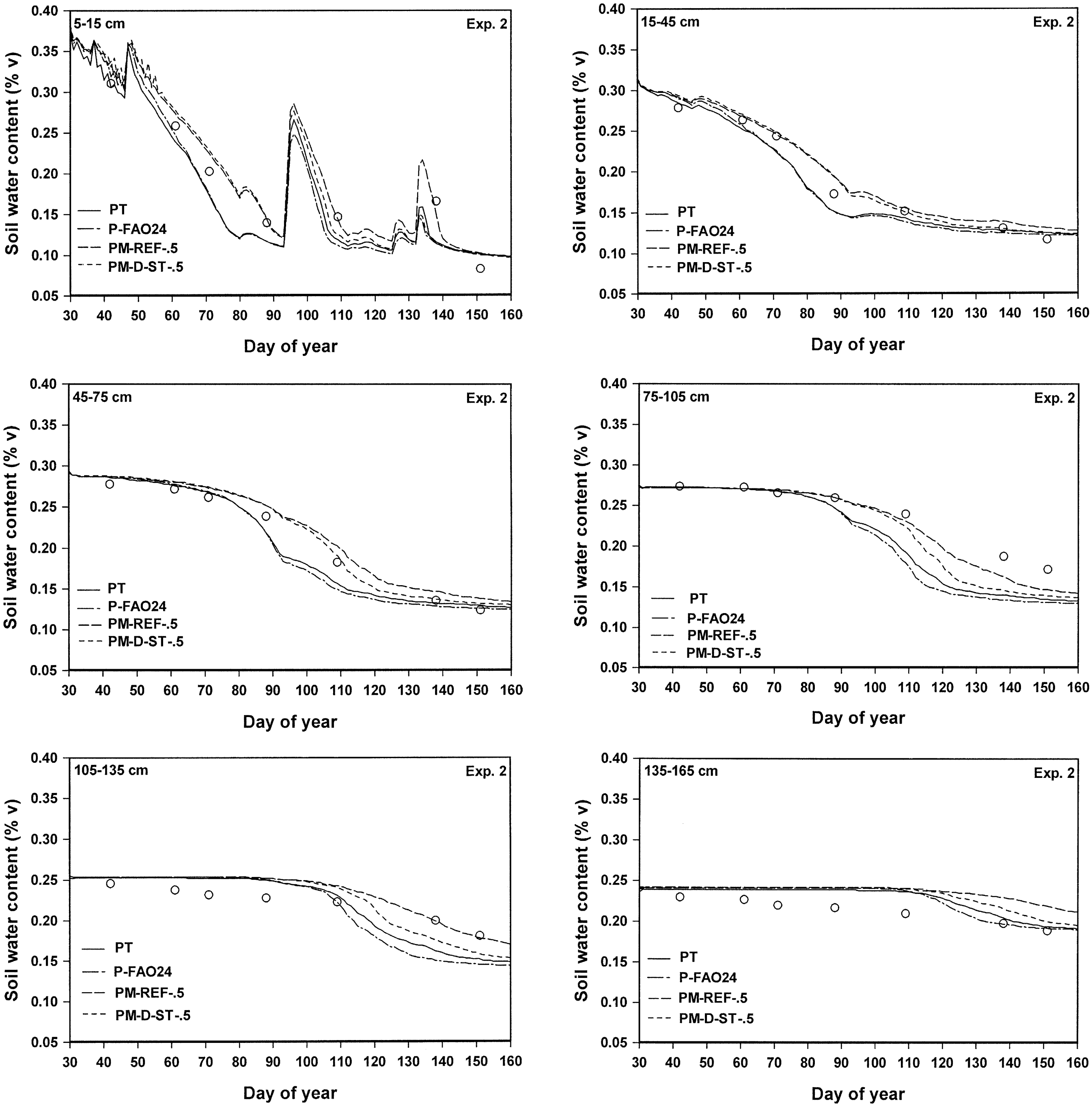


Fig. 2. Observed (points) and simulated (lines) dynamics of the soil water content (SWC) of the different soil layers during Exp. 2 rainfed season, using CROPGRO-faba bean and four evapotranspiration options: PT (1), Priestley–Taylor (Priestley and Taylor, 1972); P-FAO24 (2), modified Penman (Doorenbos and Pruitt, 1974); PM-REF-.5 (10), Penman–Monteith for the reference crop (Allen et al., 1998) with an extinction coefficient of 0.5; and PM-D-ST -.5 (14), Penman–Monteith dynamic with the bulk surface resistance calculated from leaf area index and aerodynamic resistance of the canopy calculated according to Steiner et al. (1991) and an extinction coefficient of 0.5.

of soil water extraction, cumulative ET, and cumulative crop dry matter. The PT (1) option gave reasonably good estimations of cumulative ET but was clearly not the best in terms of RMSE, *a*, *b*, or *d* values (Table 2). Likewise it predicted too much soil water extraction early in the season (Fig. 1 and 2), too high ET early in the season (high *a* value), and too much total ET (Fig. 4) although dry matter accumulation was reasonable (Fig. 5). Overprediction of ET during early season by the DSSAT crop models, using the default ET option [PT (1)], was recently reported by Nielsen et al. (2002), thus confirming what we observed here. The P-FAO24 was clearly the poorest-performing ET option, giving high intercept (*a*), high slope (*b*), significantly highest RMSE, and lowest *d* values (Tables 2 and 3). This was observed in both experimental years (results not shown). This ET option also created too much soil water extraction (Fig. 1 and 2), the highest ET (Fig. 4), and too early slowdown

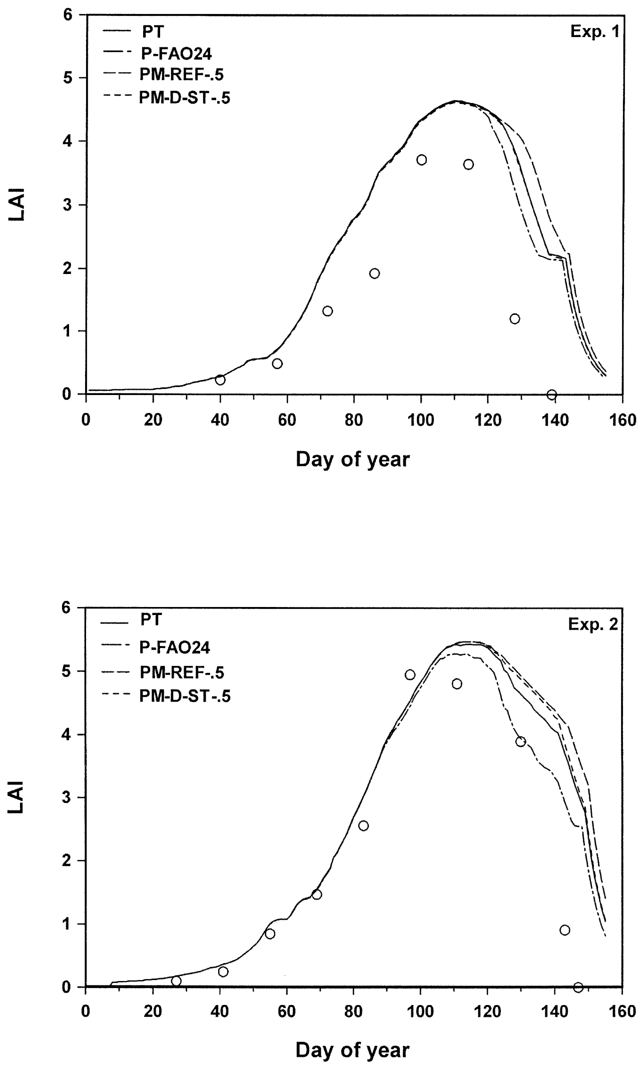


Fig. 3. Observed (points) and simulated (lines) dynamics of leaf area index (LAI) using CROPGRO-faba bean and four evapotranspiration options: PT (1), Priestley and Taylor (1972); P-FAO24 (2), modified Penman (Doorenbos and Pruitt, 1975); PM-REF-.5 (10), Penman–Monteith for the reference crop (Allen et al., 1998) with an extinction coefficient of 0.5.; and PM-D-ST-.5 (14), Penman–Monteith dynamic with the bulk surface resistance calculated from LAI and aerodynamic resistance of the canopy calculated according to Steiner et al. (1991) and an extinction coefficient of 0.5.

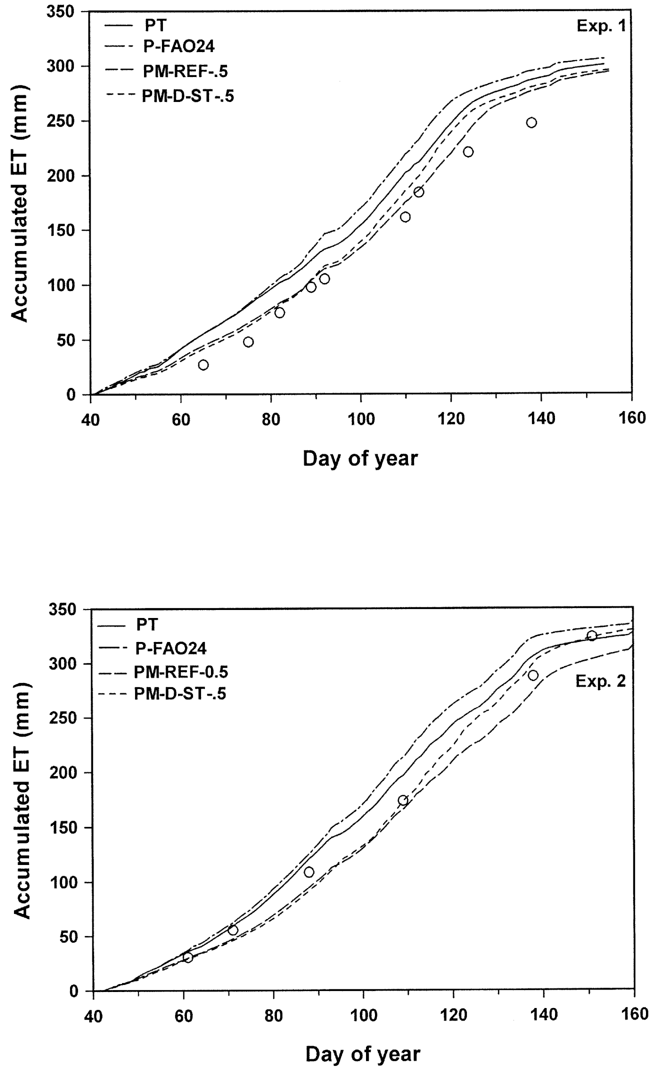


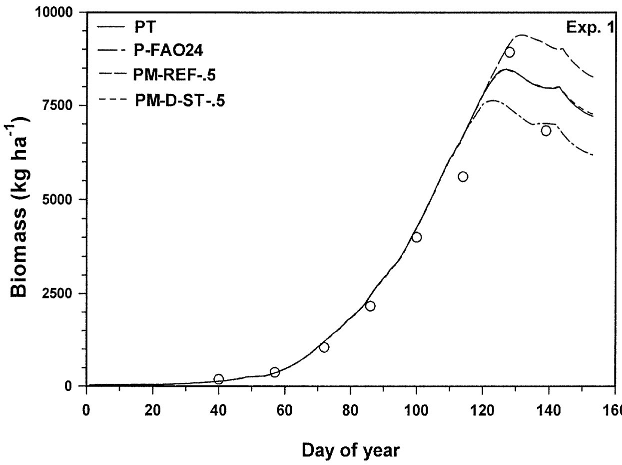
Fig. 4. Observed (points) and simulated (lines) dynamics of cumulative evapotranspiration of the crop (ET) in Exp. 1 and 2, beginning after the first neutron probe measurement [day of year (DOY) 40 in Exp. 1 and 42 DOY in Exp. 2], using CROPGRO-faba bean and four evapotranspiration options: PT (1), Priestley and Taylor (1972); P-FAO24 (2), modified Penman (Doorenbos and Pruitt, 1975); PM-REF-.5 (10), Penman–Monteith for the reference crop (Allen et al., 1998) with an extinction coefficient of 0.5.; and PM-D-ST-.5 (14), Penman–Monteith dynamic with the bulk surface resistance calculated from leaf area index and aerodynamic resistance of the canopy calculated according to Steiner et al. (1991) and an extinction coefficient of 0.5.

in dry matter accumulation (Fig. 5), giving a very poor fit to late-season biomass (Table 4). At one time, the P-FAO24 equation had been considered one of the reference ET methods and was used extensively under a large range of environments since the publication of the FAO no. 24 manual in 1974 (Doorenbos and Pruitt, 1975). However, the more recent FAO no. 56 manual (Allen et al., 1998) documents that it generally overpredicts ET, as our results also indicate.

Our mode of comparing the remainder of the ET options will be to reference the statistics in Tables 2, 3, and 4, rather than showing the predicted ET over time for all the options.

Evaluation of the Penman–Monteith Reference Evapotranspiration Options with or without Kc

The PM-REF (3) option is the same as the grass reference method proposed in the recent FAO no. 56 manual (Allen et al., 1998), assuming LAI = 2.88 at a height of 0.12 m. We need to remember that, as used in the crop model, it predicts E0, that partitioning to ES0 and EP0 depends on modeled LAI, and that (actual) ES is limited by Stage I and Stage II evaporation while EP can be limited by root water uptake. We also tried two alternate forms with Kc of 1.1 and 1.2, which effectively increase E0 by the Kc value as LAI increases from zero



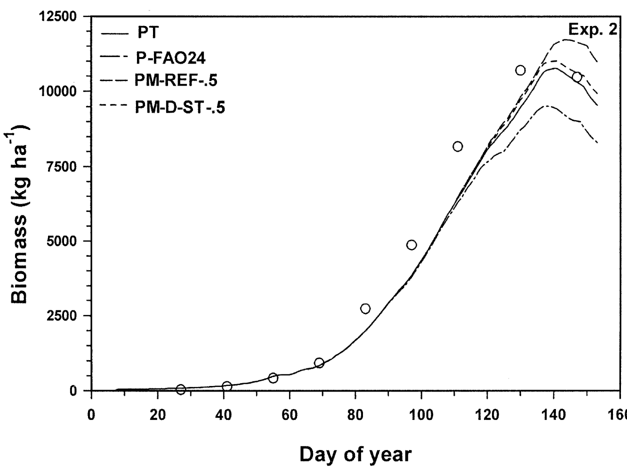


Fig. 5. Observed (points) and simulated (lines) dynamics of total aboveground biomass in rainfed crops of Exp. 1 and 2, using CROPGRO-faba bean and four evapotranspiration options: PT (1), Priestley and Taylor (1972); P-FAO24 (2), modified Penman (Doorenbos and Pruitt, 1975); PM-REF-.5 (10), Penman–Monteith for the reference crop (Allen et al., 1998) with an extinction coefficient of 0.5; and PM-D-ST-.5 (14), Penman–Monteith dynamic with the bulk surface resistance calculated from leaf area index and aerodynamic resistance of the canopy calculated according to Steiner et al. (1991) and an extinction coefficient of 0.5.

to LAImax of 6.0. The PM-REF (3) without Kc had a lower RMSE for ET (13.58) with intercept (*a*) closer to zero and *d* value closer to 1, indicating that it predicted ET better than the PT or P-FAO24 options. The smaller *a* and *b* values of the PM-REF Submodel (3), when compared with PT (1) and P-FAO24 (2) in Table 2, show that it computes a lower ET during all of the crop cycle. Root means square error was significantly smaller with PM-REF Option (3) than with options PT (1) or P-FAO24 (2) (Table 3). In terms of late-season biomass predictions (Table 4), this option predicted well and had low RMSE and high *d* values.

When the PM-REF options were attempted with Kc adjustment to increase E0 with increasing LAI, the prediction of the ET and the predictions of late-season biomass gave poorer fits as maximum Kc increased from 1.0 (Option 3) to 1.2 (Option 5), with generally higher RMSE, higher slopes (*b*), and smaller *d* values. Overall, PM-REF with Kc = 1.0 (3 or 10) or Kc = 1.1 (4 or 11) had nearly equivalent *d* values, but PM-REF 1.0 had slightly lower RMSE while PM-REF 1.1 had slope (*b*) closer to 1.0 and intercept (*a*) closer to 0.0. The prediction accuracy of these two ET options was very similar (Kc = 1.0 vs. 1.1) in both years (year-specific results not shown). A maximum value of 1.1 for Kc for faba bean is consistent with recommendations of Allen et al. (1998).

Evaluation of the Penman–Monteith Options with Dynamic Leaf Area Index and Height Effects on Aerodynamic Resistance to Water Vapor Transport

For the two dynamic PM-D options (6 and 7), the ET statistics in Table 2 (smaller *a*, lower RMSE, higher *d* value) indicate that the PM-D options were generally better estimators of ET than the PT (1) option and were certainly much better than P-FAO24 (2) option. Nevertheless, RMSE differences are only statistically significant between PM-D-ST (7) and PT (1) and not between P-D-FAO56 (6) and PT (1). In addition, only the less-water-demanding PM-D option [PM-D-ST (7), the option with higher computed Ra], concurrently also provided similar quality estimations of late-season biomass compared with the PT option (Table 3). As a consequence, PM-D-ST was the best of the PM-D options to provide a good estimation of both ET and late-season biomass.

Evaluation of Extinction Coefficient to Partition Potential Evapotranspiration to Potential Transpiration and Potential Soil Evaporation in the Evapotranspiration Options

Globally across all ET options, the use of 0.5 as general extinction coefficient (*K*) (Options 8–14) reduced early-season ET compared with default *K* of 0.85 (Options 1–7). The benefit to ET and late biomass predictions occurred in almost all the studied ET options (8–14 compared with 1–7) as seen in improvements in all statistical estimators: reduction in *a* and RMSE and *b* and *d* values closer to 1 (Tables 2 and 4). In general, the 0.5 extinction coefficient provided a major improvement in PT (1) and P-FAO24 (2) options while the apparent benefit in the PM-D options (7 and 8) was somewhat smaller (Tables 2, 3, and 4). Note that RMSE of ET obtained with P-D-FAO56 (6) was not significantly different from that obtained with P-D-FAO56-.5 (13). The benefit of using the 0.5 extinction coefficient was noticeable in both experimental years in RMSE reduction and a *d* value closer to 1 in PT, P-FAO24, and PM-D-ST (results not shown). It is important to note that E0 is predicted first and that this extinction coefficient is used for partitioning E0 to either EP0 or ES0. We conclude that it was incorrect to apply an extinction coefficient for PAR to absorption of total solar irradiance by faba bean foliage. The use of extinction partitioning coefficient of 0.5 is supported by theory (values close to 0.5 are derived from weighted average of absorption coefficients for PAR and NIR—see Materials and Methods). Furthermore, Villalobos and Fereres (1990) measured, at the same location where these faba bean experiments were conducted, a value of 0.52 for the extinction coefficient for partitioning of E0 to the transpiration component of ET for sunflower, cotton, and corn. As a result of this lower extinction coefficient, the partitioning to EP0 was lower, and computed ET was lower, primarily in early season. This had good effects to conserve water until later in the rainfed season, thus sustaining dry matter accumulation as observed in Table 4 and in Fig. 5

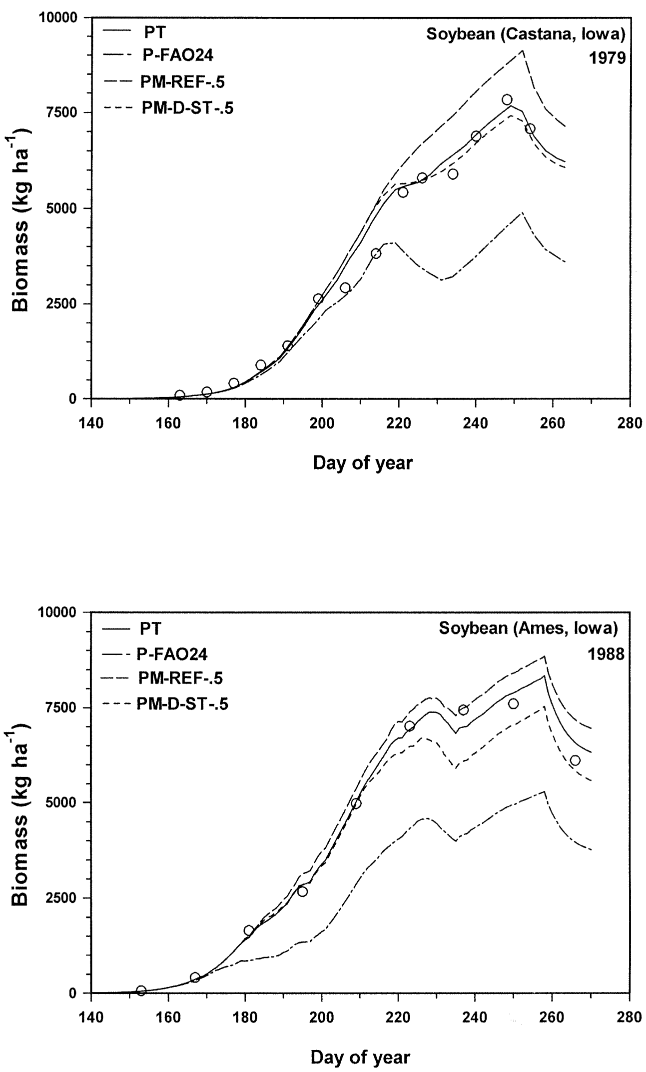


Fig. 6. Observed (points) and simulated (lines) dynamics of total aboveground biomass in rainfed crops of soybean at Castana, IA, in 1979, and Ames, IA, in 1988, using CROPGRO-soybean and four evapotranspiration options: PT (1), Priestley and Taylor (1972); P-FAO24 (2), modified Penman (Doorenbos and Pruitt, 1975); PM-REF-.5 (10), Penman–Monteith for the reference crop (Allen et al., 1998) with an extinction coefficient of 0.5; and PM-D-ST-.5 (14), Penman–Monteith dynamic with the bulk surface resistance calculated from leaf area index and aerodynamic resistance of the canopy calculated according to Steiner et al. (1991) and an extinction coefficient of 0.5.

(which compares two better ET options with 0.5 to the poorer options without 0.5).

A look to Fig. 1, 2, 3, and 4 confirms the statements above. In both years, both the PT and P-FAO24 options predicted too early and too rapid water extraction for all soil layers above 135 cm (Fig. 1 and 2). As a consequence, the cumulative ET curves (Fig. 4) showed that PT and, to a much larger extent, P-FAO24 predicted too much ET, especially during the first part of the crop cycle.

In Exp. 1 and 2, the P-FAO24 option predicted earlier water stress in the time-series–simulated growth curves than actually occurred in the field dry matter accumulation (Fig. 5). In fact, the simulated water stress effect on the growth curves was more severe in Exp. 2, and the final biomass simulated was approximately 25% smaller than that measured. The PT (1) option was mostly correct in simulation of biomass accumulation in Exp.1, but it was slightly too early in simulating a slowdown of dry matter accumulation in Exp. 2. We conclude that the P-FAO24 (2) option and, to some extent, the PT (1) option are not able to satisfactorily predict ET and the soil water content time series of the different soil layers, and as a consequence, the crop model underpredicts dry matter under conditions of limited water availability, a situation found in a large majority of rainfed crops.

Figures 1, 2, 3, and 4 show the progressive improvement on the accuracy of the predicted dynamic course of soil water content, ET, and biomass predicted by the crop model as we change ET equations from the worst, P-FAO24 (2), to PT (1), and finally to the best, PM-REF-.5 (10) or PM-D-ST-.5 (14). Both PM-REF-.5 and PM-D-ST-.5 give very good predictions and timing of these variables. Theoretically, all the Penman–Monteith–related ET equations have the advantage over the PT method in their sensitivity to the advective effect of high VPD and wind speed. A Mediterranean winter crop such as faba bean passes from a low-VPD environment in early season to high VPD during pod filling, so Penman–Monteith ET equations that are able to capture this important driving factor of water loss seem to be more advisable. In Fig. 4, we assumed that runoff and drainage were null, but if these assumptions do not hold, then actual ET values would be lower than the plotted values but would still be much closer to the new proposed methods (10 and 14).

Testing Four Evapotranspiration Options on Soybean in the USA

It is important that these ET options be tested in a wider range of environments. Their inclusion in the DSSAT program will facilitate their testing by a wider range of model users. As an initial start to this effort, we tested these same four ET options with data sets on soil water and dry matter accumulation of soybean for Ames, IA (1988 drought season); Gainesville, FL (1978 drought season); and Castana, IA (1979 moderate drought, but no deep soil water drainage). The Gainesville and Castana data sets are the same as described by Calmon et al. (1999) while the Ames data are unpublished (R.M. Shibles, unpublished, 1988). At these three sites with a different crop, the P-FAO24 (2) consistently overpredicted soil water extraction and ET, with the consequence that it clearly underestimated biomass accumulation and predicted stress sooner than occurred in the observed data, especially for Ames and Castana sites (Fig. 6). The P-FAO24 (2) gave even worse biomass predictions for soybean in Iowa in a windy season (wind speed average during growing season approximately 250 km d^{-1}) than for faba bean in a less windy location (southern Spain, wind speed average during growing season approximately 150 km d^{-1}) (Fig. 5 and 6). The PT (1) option generally performed satisfactorily for all three sites for predicting soil water content and dry matter accumulation. The dynamic PM-ST-.5 (14) version predicted soil water extraction and dry matter accumulation as well as the PT option for Castana and Ames sites but slightly underpredicted soil water extraction and slightly overpredicted dry matter for the more humid Gainesville, FL, location. As for faba bean, PT (1) and PM-ST-.5 (14) gave soybean simulations with very similar biomass accumulation predictions (Fig. 5 and 6). In contrast to the faba bean simulations, the PM-REF-.5 (10) option generally underpredicted water extraction and ET of soybean, with the consequence that dry matter accumulation was not reduced enough by the simulated water deficit (Fig. 6). For the PM-REF-.5 option for soybean, use of Kc coefficients of 1.1 (Ames), 1.2 (Castana), and 1.3 (Gainesville) worked best (simulations not shown). Even with faba bean, a Kc of 1.1 performed well; thus, the use of a crop coefficient that allows increasing ET as function of LAI, as described in Options (4), (5), (11), and (12), would improve predictions with this option.

CONCLUSIONS AND RECOMMENDATIONS

We conclude from the tested ET options that, for these environments and crops, PT (1) is reasonable but tends to overpredict ET, especially in early season, and would benefit from use of 0.5 extinction coefficient. With this change, the PT should remain a satisfactory option, particularly when weather data such as wind speed and humidity are not available. Second, the P-FAO24 (2) is the least adequate to simulate ET and biomass. The literature generally agrees that this E0 estimator tends to overpredict and as a consequence overpredicts water stress under a wide range of environments. Our results confirm this; therefore, we recommend deleting the P-FAO24 option from the DSSAT crop models. The PM-REF-Kc option has been included in the DSSAT V4.0 release because it gave excellent ET and biomass predictions for these data sets, allows Kc to vary as a function of the LAI of the crop, and is close to the present FAO-recommended method. Actually, Penman–Monteith reference options performed well—(3) Kc = 1.0, (10) Kc = 1.1, (11) Kc = 1.1, and (12) Kc = 1.2—and were not different from each other in the tested environment for faba bean. Since crop models can supply dynamic time course of LAI and crop height, we recommend inclusion of PM-D-ST (7) as the best of the dynamic versions that use the Penman–Monteith equations. Under the tested conditions, this dynamic version had generally better performance than the PT (1) option and was comparable to or better than the PM-REF-.5 option (10). These dynamic options of the Penman–Monteith will facilitate further possibilities of allowing Rs to be modified as a function of crop physiological, nutritional, and environmental factors.

Due to the general benefits on ET and late-season biomass predictions with the 0.5 extinction coefficient observed in the faba bean environment, and because a smaller extinction coefficient than the original (0.85) is supported by total SR extinction theory and literature reports, we recommend testing lower K (≈0.5) in a wide range of crops and environments before generalizing its use in the DSSAT models' ET/water balance options. Reducing K value may be particularly beneficial for the PT option where the simulations were significantly improved by its use.

APPENDIX: SUMMARY OF ABBREVIATIONS

a	intercept of linear regression
AC	weighting factor for Rs and Ra
ALBEDO	crop albedo
b	slope of linear regression
Cp	specific heat of the air at constant pressure (MJ kg °C^{-1})
d	zero plane displacement height (m)
d	index of agreement
DAS	days after sowing
DOY	day of year
DSSAT	Decision Support System for Agrotechnology Transfer
DUL	drained upper limit or field capacity of soil (% vol.)
E0	potential evapotranspiration of the crop and soil (mm)
EEQ	equilibrium evapotranspiration (mm)
EP	transpiration of the crop (mm)
EP0	potential transpiration of the crop (mm)
ES	soil evaporation (mm)
ES0	potential soil evaporation (mm)
ET	actual evapotranspiration of the crop (mm)
ETc	crop evapotranspiration under standard conditions (mm)
ETo	reference evapotranspiration (mm)
G	soil heat flux density (MJ m^{-2} d^{-1})
H	crop height (m)
K	crop extinction coefficient for solar radiation
K_{bl}	leaf extinction coefficient for radiation if the leaf is opaque
Kc	crop coefficient
Kcb	basal crop coefficient
Ke	soil evaporation coefficient
LAI	leaf area index
LAImax	maximum leaf area index
LL	soil water content at the lower limit or permanent wilting point (% vol.)

NIR	near infrared radiation
PAR	photosynthetically active radiation
Ra	aerodynamic resistance to water vapor transport (s m^{-1})
Ra-crop	aerodynamic resistance to water vapor transport of the crop (s m^{-1})
Ra-soil	aerodynamic resistance to water vapor transport of the soil (s m^{-1})
Ra-total	aerodynamic resistance to water vapor transport of the soil and crop (s m^{-1})
Rl	leaf resistance to water vapor transport (s m^{-1})
RMSE	root mean square error
Rn	net radiation (MJ m^{-2} d^{-1})
Rs	surface resistance to water vapor transport (s m^{-1})
Rs-crop	surface resistance to water vapor transport of the crop (s m^{-1})
Rs-soil	surface resistance to water vapor transport of the soil (s m^{-1})
Rs-total	surface resistance to water vapor transport of the soil and crop (s m^{-1})
RWU	potential root water uptake of the crop (mm d^{-1})
SAT	soil water content at saturation (% vol.)
SR	daily total solar radiation (MJ m^{-2} d^{-1})
SWC	soil water content (% vol.)
SWFAC	photosynthesis water stress factor
Tavg	daily average temperature (°C)
Tmax	daily maximum temperature (°C)
Tmin	daily minimum temperature (°C)
TURFAC	turgor stress factor
U_2	wind speed at 2 m height (m s^{-1})
U_{2g}	wind speed at 2 m over grass (m s^{-1})
U_{2s}	wind speed at 2 m above the crop (m s^{-1})
VPD	water vapor pressure deficit (kPa)
WR(L)	soil rooting preference function
Zoh	roughness length governing heat-and-water vapor (m)
Zom	roughness length governing momentum (m)
Zr	reference height for wind speed relative to the crop (m)
α	advectivity coefficient
γ	psychrometric constant (kPa $°C^{-1}$)
Δ	slope of the saturation water vapor pressure (kPa $°C^{-1}$)
ρa	mean air density at constant pressure (kg m^{-3})
σ	leaf scattering coefficient

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