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Model for Estimating Evaporation and Transpiration from Row Crops

By Francesca Ventura,[1] Ben A. Faber,[2] Khaled M. Bali,[3] Richard L. Snyder,[4] Donatella Spano,[5] Pierpaolo Duce,[6] and Kurt F. Schulbach[7]

Abstract: Accurate estimates of crop evapotranspiration ET_c, that quantify the total water used by a crop, are needed to optimize irrigation scheduling for horticultural crops and to minimize water degradation. During early growth, accurate assessments of ET_c are difficult in vegetable crops because of high soil evaporation due to frequent irrigation. A model to estimate ET_c for vegetable crops, using only daily reference evapotranspiration data as an input parameter, was developed. It calculates crop transpiration and soil evaporation based on ground cover and daily radiation intercepted by the canopy. The model uses a two-stage soil evaporation method adapted to conditions of variable reference evapotranspiration. The model was evaluated against data using measurements from two seasons of lettuce crop, two tomato fields in the same season, and one season of broccoli crop production. Using all of the crop data, the root-mean-square error for measured versus modeled daily ET_c was 0.72 mm day^{-1}, indicating that the model works well.

INTRODUCTION

Horticultural crops are widely cultivated in regions with a Mediterranean climate, where irrigation is available. The annual growth habit and shallow rooting of many of these crops (i.e., vegetables) often requires frequent irrigation, which may lead to excessive water use, low irrigation efficiency, and groundwater contamination from nitrate and pesticide leaching. Accurate estimates of crop evapotranspiration ET_c are important to optimize irrigation scheduling, enhance efficiency, and prevent groundwater pollution.

When row crops are in an early stage, ET_c is dominated by soil evaporation rate. Later, the plant cover increases and the evapotranspiration rate is dominated by transpiration from the plants. Commonly, ET_c is estimated by multiplying a reference evapotranspiration ET_0, calculated from meteorological data, by a crop coefficient K_c, which accounts for crop factors and management. Crop coefficient K_c values account for irrigation and rainfall frequency; however, because of the difficulty in estimating soil evaporation, an average K_c value is often used during early growth of row crops to account for wetting frequency. Several models able to separately estimate evaporation from the soil E and crop transpiration T are available in the literature. Most of them are analytical models (Van Bavel et al. 1984; Shuttleworth and Wallace 1985) and require many crop and soil parameters that are not commonly available. An E and T model for lettuces (Gallardo et al. 1996) was previously developed, but the lettuce canopy is unique relative to other horticultural crops. In this paper, a model that is similar to the Gallardo et al. (1996) model, but improved to account for irrigation method and different canopies, is presented. The advantage of this model is that the only daily input parameter required is ET_0.

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MODEL DESCRIPTION

The model separates ET_c into E and T by assuming the ratio of the maximum T to ET_c rate is the same as the fraction of total daily solar radiation intercepted by the canopy. The solar radiation that is not intercepted by foliage contributes to soil evaporation, but the E rate also depends on soil wetness and hydraulic properties. It is assumed that convective energy contributes to E and T in a similar proportion as radiation. This is a fair assumption because the percentages of canopy ground cover and light interception are similar. In the model, T is related to the percentage of solar radiation that is intercepted by the crop canopy R_i, which is estimated as a function of the percentage of ground covered by the canopy. The percentage ground cover on each day C_i is estimated as a function of cumulative ET_0.

Soil evaporation is a two-stage process (Lemon 1956; Idso et al. 1974). During stage 1 the evaporation rate depends only on the energy available to vaporize water. Eventually, the soil dries to stage 2 and the evaporation rate is limited by soil hydraulic properties. The soil evaporation rate depends on the fraction of the exposed soil that is wetted by irrigation and the percentage of light reaching the wet surface. This depends on the irrigation method and the location of wetted surface relative to the canopy. Soil that is not wet or exposed to sunlight is assumed to have zero evaporation. Evaporation is separated into stages 1 and 2 only for wet, exposed soil.

Modeling of Canopy Development

The ground cover percentage on the ith day C_i is used to estimate radiation interception by the plants. A sigmoidal function was used to estimate crop ground cover development during the season (Charles-Edward et al. 1986), with normalized cumulative ET_0 N_i as the input parameter. Substitution of N_i for degree-days gives good results because there is a high correlation between N_i and normalized degree-days, i.e., heat units. Normalized cumulative N_i is calculated as

$$N_i = \sum_{j=1}^{i} ET_{0j}/ET_{on} \quad (1)$$

where j = number of days after planting date; and ET_{0n} = cumulative ET_0 at the end of the season. Ground cover C_i values are determined from seeding or transplanting until the maximum ground cover is reached. For lettuce and broccoli, this occurs at or near the end of the season. For tomatoes, the maximum ground cover occurs during midseason. The percentage ground cover is normalized as $P_i = C_i/C_n$, where C_i is the observed ground cover on the ith day and C_n is the maximum ground cover percentage for the season. In the model, P_i is estimated as a sigmoidal function of N_i and the percentage ground cover on the first day of the season P_1

$$P_i = P_1 + \frac{1 - P_1}{1 + e^{a+bN_i}} \quad (2)$$

After determining P_i, ground cover percentage is calculated as $C_i = P_iC_n$.

Radiation Interception and Transpiration

Percentage radiation interception by the canopy on the ith day is calculated from the modeled C_i using a relationship experimentally determined by Hernandez-Suarez (1988) using a wide range of agronomic crops

$$R_i = 0.63 + 1.373C_i - 0.0039C_i^2 \quad (3)$$

Therefore, the fraction of daily radiation intercepted by the canopy on the ith day is $R_i/100$, and the fraction of radiation intercepted by the soil is $(1 - R_i/100)$.

Transpiration from the crop is estimated as the product of the maximum possible ET_c on the ith day ET_{xi} and the fraction of radiation intercepted by the canopy

$$T_i = ET_{xi}\left(\frac{R_i}{100}\right) \quad (4)$$

where ET_{xi} is estimated as the product of ET_{0i} and the maximum possible K_c on the ith day. The maximum K_c corresponds to stage 1 soil evaporation or to the maximum crop evapotranspiration, whichever is bigger on the ith day of the season.

Soil Evaporation without Crop

Soil evaporation is modeled as a two-stage process, where stage 1 is limited by energy availability and stage 2 is limited by soil wetness and hydraulic properties (Ritchie 1972; Boesten and Stroosnijder 1986; Stroosnijder 1987; Ritchie and Johnson 1990; Burman and Pochop 1994; Gallardo et al. 1996). During stage 1, the soil is sufficiently wet for the water to be transported to the surface at a rate equal to ET_{xi} for bare soil. Therefore the stage 1, bare soil evaporation on the ith day after irrigation $E1_i$ is limited only by the supply of energy for vaporization and

$$E1_i = ET_{0i}K_s \quad (5)$$

The wet soil crop coefficient K_s is estimated using the initial growth period 2-day wetting frequency K_c versus ET_0 curve presented by Doorenbos and Pruitt (1977). A linear regression of K_c versus ET_0 using that data gave

$$K_s = 1.05 - 0.03ET_0 \quad (6)$$

Starting immediately after an irrigation, a plot of cumulative soil evaporation CE_i or cumulative maximum soil evaporation $CE1_i$, whichever is smaller, versus the square root of the cumulative stage 1 evaporation $\sqrt{CE1_i}$ is used to determine the soil hydraulic factor β, which is used to estimate soil evaporation during stage 2 evaporation. While in stage 1, the data points lie along the $y = x^2$ curve, and they diverge and follow a linear trend as soon as the soil reaches stage 2 evaporation. The $\sqrt{CE1_i}$ value where the evaporation changes from stage 1 to stage 2 is the hydraulic factor β. The slope of the linear, stage 2 portion of the CE_i curve is also equal to β. The hydraulic factor is found by eliminating the data pairs that fall in stage 1 evaporation and calculating a linear regression through the remaining data. Data pairs are eliminated until the minimum $\sqrt{CE1_i}$ is bigger than the slope of the linear regression through the origin of all remaining data pairs.

Once experimentally determined for a field, β is used to calculate the onset of stage 2 evaporation and CE_i during stage 2. For all values of $\sqrt{CE1_j} > \beta$, stage 2 soil evaporation rate for the pth half-hour is calculated as $E_{sp} = E2_p$, where

$$E2_p = \beta\left(\sum_{j=k}^{p} E1_j\right)^{1/2} - \beta\left(\sum_{j=k}^{p-1} E1_j\right)^{1/2} \quad (7)$$

Following a new irrigation or a rainfall the evaporation rate returns to stage 1. Note that the soil evaporation model described above will underestimate CE_i slightly at low ET_0 rates and the error can increase to as much as 10% at the end of stage 1 when the ET_0 rates are high, i.e., $ET_0 > 8.0$ mm day^{-1}. The error is small when used for separating ET_c into E and T.

Soil Evaporation with Crop

Sprinkler Irrigation or Rainfall

When a crop is present over a soil that is completely wetted by sprinkler irrigation or rainfall, then the soil evaporation E_i is estimated by adjusting E_{si} for the percentage of solar radiation reaching the wetted surface $(100 - R_i)$

$$E_i = E_{si}\left(1 - \frac{R_i}{100}\right) \quad (8)$$

Only the fraction of solar radiation that is not intercepted by the canopy is assumed to reach the surface, and only the fraction of the soil surface receiving the solar radiation that is wet is assumed to contribute to soil evaporation. The shaded soil surface area between the furrow middles shown in Fig. 1 approximately represents the area that would contribute to soil evaporation if wet.

Trickle (Drip) Irrigation

Generally, when surface drip systems are used to irrigate field and row crops, there is one drip line per bed. However, there can be one or two rows of plants in each bed depending on the crop. In both cases, assume that the beds comprise B% of the total surface area and that the drip line lies in the middle of the bed.

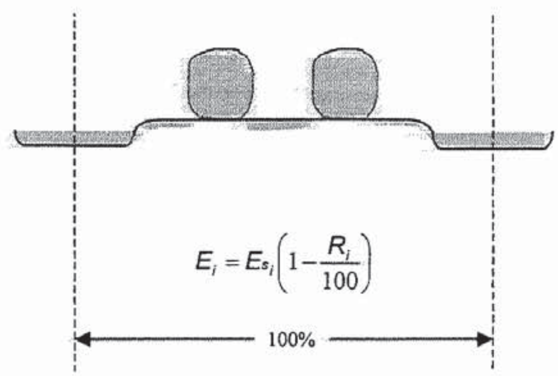

FIG. 1. Canopy Effect on Soil Evaporation from Sprinkler-Irrigated Row Crops or Crops Receiving Rainfall: Wetted Soil Surface That Receives Radiation Is Shadowed

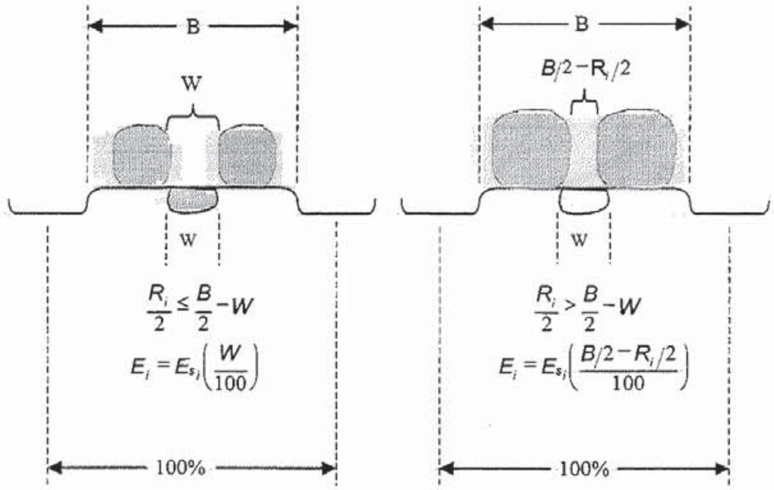

FIG. 2. Canopy Effect on Soil Evaporation from Drip-Irrigated Row Crops: (Left) Entire Wetted Surface Receives Sunlight; (Right) Canopy Reduces Sunlight Penetration to Wetted Surface

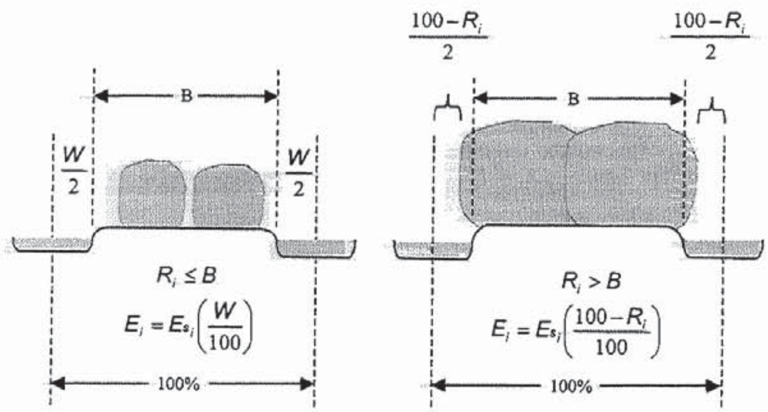

FIG. 3. Canopy Effect on Soil Evaporation from Furrow-Irrigated Row Crops: (Left) Entire Wetted Surface Receives Sunlight; (Right) Canopy Reduces Sunlight from Reaching Wetted Furrows

When there are two rows of plants per bed and they are planted at 1/3 and 2/3 of the bed width, then the wetted surface area is exposed until the canopy grows sufficiently to cover the wet surface. This is illustrated in Fig. 2. If W is the percentage of total area that is wetted, R_i is the percentage of light interception by the canopy, and $R_i/2 \le B/2 - W$, then the soil evaporation is

$$E_i = E_{si}\left(\frac{W}{100}\right) \quad (9)$$

If $R_i/2 > B/2 - W$, then the soil evaporation is given by

$$E_i = E_{si}\left(\frac{B/2 - R_i/2}{100}\right) \quad (10)$$

However, when $R_i > B$, then $E_i \approx 0$.

When there is only one row of plants per bed and both the plant row and the drip line are centrally located in the bed, then the canopy starts to affect evaporation as soon as it emerges and begins to block sunlight from the surface. Using the same symbols as before, the soil evaporation E_i is calculated as

$$E_i = E_{si}\left(\frac{W - R_i}{100}\right) \quad (11)$$

However, when $R_i > W$, then $E_i \approx 0$. In this paper, only the case with one row of plants per bed was investigated.

Furrow Irrigation

For furrow irrigation, again it is necessary to estimate the exposed, wetted soil surface area. The percentage wetted area W is first determined from the midpoint of one furrow to the next (Fig. 3). For example, if the area in the wetted perimeter of the irrigated furrows is 40% of the total area, then W = 40%. If every second furrow is irrigated and the area in the wetted perimeter is 20%, then W = 20%. The wetted surface is not considered shaded until the light interception exceeds the percentage area for the planting bed B. Therefore, if $R_i \le B$, then

$$E_i = E_{si}\left(\frac{W}{100}\right) \quad (12)$$

When $R_i > B$, then

$$E_i = E_{si}\left(\frac{100 - R_i}{100}\right) \quad (13)$$

Crop Evapotranspiration

After determining the transpiration and soil evaporation rates, crop evapotranspiration on the *i*th day is calculated as

$$ET_{ci} = E_i + T_i \tag{14}$$

MATERIAL AND METHODS

Crop Growth

The a and b empirical parameters in (2) were determined with ground cover measurements using a photographic technique. Data were collected during the growth of 21 vegetable crops (Tables 1–3) that were planted at different times of the year in three locations in California (Salinas Valley, the Oxnard Plain, and the Imperial Valley). Climatically, the sites are located along the foggy central coast, the mixed foggy and sunny south coast, and in a below sea level desert (during winter). The camera was fixed on top of a 3.0-m-long pole, taking care to keep it perpendicular to the vegetation surface. Photographs were taken every 7–10 days and were scanned and image processed to estimate the percentage of area covered by the crop canopy. These data, together with the daily ET_0 collected from nearby California irrigation management information system stations (Snyder and Pruitt 1992), were used to estimate the a and b coefficients in (2).

Soil Evaporation

Actual evapotranspiration ET_a experimental data were obtained by measuring the energy balance over several crops and calculating the latent heat flux density ($LE = ET_a$), which equals ET_a

$$LE = R_n - G - H \tag{15}$$

Net radiation R_n and soil heat flux G were measured using respectively a net radiometer (model Q-7.1, REBS Inc.) 1.5 m above the soil and soil heat flux plates (model HFT3, REBS Inc.), sensible heat flux H was measured directly with the eddy covariance method (Monteith and Unsworth 1990; Brutsaert 1984). Eddy covariance requires simultaneous measurements of the fluctuating components of wind and temperature in the constant flux region over the surface. The instantaneous turbulent flux of both these quantities has generally a vertical component; if there is a net transport of heat toward or away from the surface the fluctuations of the two quantities are correlated. Measuring both the temperature and wind fluctuations, with a 1D sonic anemometer (model CA27, Campbell Scientific Inc.) and computing the correlation over a suitable time period provides a measure of H to use in (15) to determine $LE = ET_a$. When sonic anemometer data were unavailable, H was estimated using the surface renewal method (Paw U et al. 1992; Snyder et al. 1996; Spano et al. 1997). Half-hourly soil evaporation data were measured where model validation was performed to determine the β parameters. In each case, data were collected as the soil dried after a heavy irrigation.

TABLE 1. Crop Characteristics Used to Calculate Percentage of Ground Cover for Early Planted Crops (Early Winter to before Summer Solstice Plantings)

Crops planted	Planting date	Season (days)	ET_0 (mm)	C_n (%)	RMSE (observed versus modeled)
"Ventura" broccoli	12/19/96	99	190.5	100	0.082
"Huntington" broccoli	4/5/95	94	478.4	100	0.110
Spring lettuce 1	1/16/95	100	242.3	70	0.117
Spring lettuce 2	2/8/95	90	302.8	64	0.071
Spring lettuce 3	3/2/95	79	324.9	70	0.067
Winter lettuce	12/17/94	115	287.8	70	0.087
Spring lettuce	4/12/94	62	339	72	0.096
Summer lettuce (1)	5/7/94	61	362	72	0.148
Summer lettuce (2)	5/4/94	66	367	74	0.094
Winter lettuce (thinned)	11/20/95	129	291.6	65	0.076
Overall	—	—	—	—	0.094

Note: Growth coefficients are $a = 5.886$ and $b = 10.030$.

TABLE 2. Crop Characteristics Used to Calculate Percentage of Ground Cover for Transplanted Crops (with Initial Ground Cover >0)

Crops planted	Planting date	Season (days)	ET_0 (mm)	C_n (%)	RMSE (observed versus modeled)
"Huntington" celery	4/5/95	110	580.8	85	0.036
"Royal" cauliflower	1/19/95	107	254.1	70	0.071
"Huntington" tomato	4/17/95	120	652.9	100	0.075
"Ventura" tomato	4/4/96	120	353.7	65	0.098
"Ventura" red cabbage	4/1/96	83	109.1	86	0.058
Overall	—	—	—	—	0.073

Note: Growth coefficients are $a = 4.946$ and b −9.538.

TABLE 3. Crop Characteristics Used to Calculate Percentage of Ground Cover for Late Plantings (after Summer Solstice)

Crops planted	Planting date	Season (days)	ET_0 (mm)	C_n (%)	RMSE (observed versus modeled)
"Huntington" broccoli 2	7/1/95	88	401.2	100	0.077
"Royal" lettuce	6/29/95	63	358.1	65	0.034
"Huntington" lettuce (big)	7/17/95	72	360.1	70	0.120
"Huntington" lettuce (medium)	7/29/95	72	340.5	65	0.580
"Huntington" lettuce (small)	8/12/95	74	313.9	75	0.028
"Petite" celery	7/5/95	97	533.7	100	0.028
Overall	—	—	—	—	0.081

Note: Growth coefficients are $a = 8.173$ and $b = -12.065$.

Estimating Soil Hydraulic Factor β

In experiments to determine β, the soil evaporation was measured each half-hour, so the subscript j represents the jth half-hour sample. The square root of the cumulative stage 1 evaporation through the pth half-hour is given by $\sqrt{CE1_p} = \sqrt{\sum_{j=k}^{p} E1_j}$, where the initial value for k is 1. The slope of CE_j versus $\sqrt{CE1_j}$ is calculated first for $j = m$ to n, where m gives a value for $\sqrt{CE1_j}$ that is slightly less than the value of the point where the plot of CE_j versus $\sqrt{CE1_j}$ separates from the curve of $CE1_j$ versus $\sqrt{CE1_j}$ and becomes linear, and n is the total number of half-hour samples. This is illustrated in Fig. 4 where the dotted line is the linear regression of all data pairs with the x value $>\sqrt{CE1_j} = 3.00$. Clearly, this does not represent where the measured data separate from the curve of $CE1_j$ and become linear. A second minimum x value was selected as $\sqrt{CE1_j} = 4.00$ and a new linear regression was calculated (solid line in Fig. 4). The minimum x value is still to the left of the curved $CE1_j$ line, so a higher minimum value is still needed. Note that the slope increased slightly as a higher value for the minimum x value was used, but the difference between the slope and minimum x value decreased. To find β, the minimum x value is increased until it is bigger than the slope of the regression. In this example, the dashed line with the minimum x value of 4.05 has a slope of 4.02, so a $\beta = 4.02\ \text{mm}^{0.5}$ is selected for this soil.

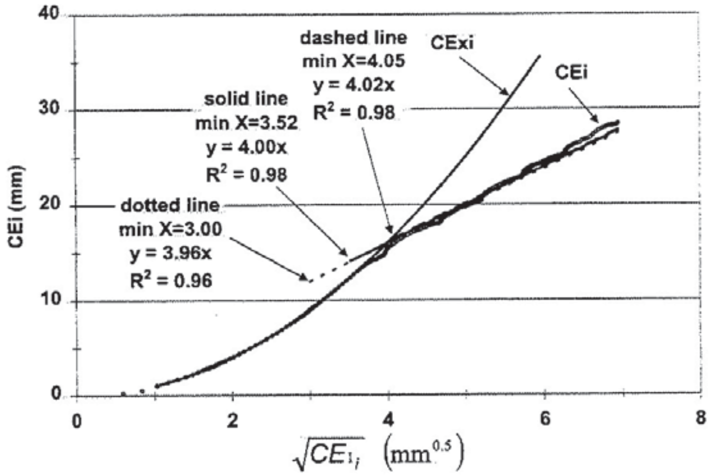

FIG. 4. Measured Cumulative Soil Evaporation CE_i or Cumulative Maximum Stage 1 Evaporation $CE1_i$ versus Square Root of Cumulative Maximum Stage 1 Evaporation ($\sqrt{CE1_i}$) from Flood-Irrigated Field in Imperial Valley, Calif.

Estimating Soil Evaporation Using β and Daily Data

The same soil evaporation relationships apply for daily as well as for hourly or half-hourly data. Eq. (5) is used to estimate soil evaporation when the square root of the cumulative daily stage 1 evaporation is <β, i.e., $\sqrt{CE1_i} \leq \beta$ on the *i*th day after irrigation. When the square root of the cumulative stage 1 soil evaporation is >β (i.e., $\sqrt{CE1_i} > \beta$ on the *i*th day after irrigation), then (16) is used

$$E2_i = \beta \left(\sum_{j=1}^{i} E1_j \right)^{1/2} - \beta \left(\sum_{j=1}^{i-1} E1_j \right)^{1/2} \qquad (16)$$

where the subscript j = number of days after irrigation.

Model Validation

The model was evaluated making comparison with actual evapotranspiration ET_a data measured on three different crops: lettuce (*Lactuca sativa*) during 2 years in the same plot; tomato (*Solanum esculentum*) in two locations during the same year; and broccoli (*Brassica olearacea*). The growing conditions at each site are summarized in Table 4. The ET_a data in the five experiments were determined using the energy balance and eddy covariance methods as described earlier. Evapotranspiration was measured hourly and summed to obtain daily values.

Lettuce

Lettuce ET_c data were measured at the University of California experimental farm in Imperial Valley, Calif. (32°50′N, 115°30′W), which is the desert below sea level in an irrigated area. Crop evapotranspiration was measured both years on the same plot (60 × 60 m) with a fetch of 37 m. Not all the data obtained were considered to be reliable, due to the meteorological condition, and 13 days of ET_c on the first year, and 39 on the second, were used for the model validation.

Tomato

The first experiment on tomatoes was carried out in a commercial farm in Ventura, Calif. (34°20′N, 119°20′W). This area is characterized by a humid and foggy climate in summer, with clear skies only during the central part of the day. The ET_c was measured using eddy covariance and energy balance with a fetch of 160 m.

The second tomato experiment was conducted in a commercial field in Oristano, Italy (39°50′N, 8°35′E), in an area that is characterized by a warm, humid climate. Measurements were taken on a 50 × 200 m plot with 45-m fetch. The ET_0 data were estimated using the Penman-Monteith equation (Allen et al. 1994) and weather data from the University of Sassari experimental farm, which is located 4 km from the field.

Broccoli

The ET_c measurements on broccoli were collected near Ventura, Calif., on the same farm where the tomato data were taken, in a 200 × 200 m plot with 100-m fetch.

RESULTS

Ground cover data from 21 crops grown in all seasons over several years were collected and divided into groups according to planting period. In addition, transplanted crops were separated from sowed crops. Differences in growth among crops

TABLE 4. Crop and Irrigation Characteristics for Sites Used to Estimate ET_c

Crop	Planting date	Harvest date	Irrigation number	Irrigation system	Measurement dates
"Crisphead" lettuce	11/20/95 (Th. 9/1/96)	3/27/96	10	Sprinkler (3); furrow (7); B = 60%	From 12/1/95 to 2/28/96
"Winterhaven" lettuce	9/17/96 (Th. 11/12)	2/5/97	14	Sprinkler (8); furrow (6); B = 60%	From 10/25/96 to 2/4/97
"3155" tomato	4/4/96 (transplanted)	8/8/96	6	Furrow; B = 60%	From 4/4/96 to 4/6/96
"Rossa" tomato	5/16/97 (transplanted)	8/25/97	14	Sprinkler (3); drip (11); W = 30%	First: From 5/30/97 to 6/1/97; Second: From 7/8/97 to 7/13/97
"Green Belt" broccoli	12/19/95	4/15/96	2 (+7 rain)	Sprinkler	From 4/5/96 to 4/9/96

Note: Th. = thinning date; B = bed area percentage.

were not evident, but the crop development varied depending on the growing season. Transplanted crops had a slower initial growth rate than sown crops.

Percentage of ground cover during the various seasons were calculated using (2) and the results were compared to measured values. The model simulated the crop development with a root-mean-square error (RMSE) within 11% of the estimated ground cover, as shown in Tables 1–3. The a and b coefficients are given in the footnotes of Tables 1–3.

The β factor was determined for each experimental site where ET_a was measured using one dry-down cycle. It would be useful to establish a functional relationship between the β factor and one or more soil hydraulic characteristics that are easier to evaluate, but unfortunately β was unrelated to soil texture (Table 5) and infiltration rate (Boesten and Stroosnijder 1986; Snyder et al. 2000). More research is needed to determine which soil physical factors affect the β parameter; at this time it seems that a micrometeorological method to estimate soil evaporation during a dry-down cycle provides the best procedure to determine β.

The E and T model was evaluated against ET_a data using measurements from five plots including crops of lettuce, tomato, and broccoli (Figs. 5–7). The figures show the modeled ET_c during the growing season, measured ET_a values, and irrigation and rainfall events (I&R) in the lower part and the two modeled ET_c components, E and T, in the upper part. In all cases, the E contribution to ET_c was considerable at the beginning of the season and became progressively less important, or approached zero, with the crop growth. Fig. 6 shows that soil evaporation from the 1997 tomato crop approached zero very early in the season when the percentage of soil wetted by the drip irrigation became smaller than the soil covered by the canopy. With the other crops E contributed to ET_c whenever irrigation was applied. Experimental data were taken during low T periods—at the beginning of the season, and during low E periods—at the end of the season, and the model seems to fit both situations well. The RMSE values for measured versus modeled ET_c were 0.63 mm day^{-1} for lettuce, 0.55 mm day^{-1} for tomato, and 0.54 mm day^{-1} for broccoli.

Measured ET_a data in all five experiments versus the corresponding model estimates are plotted in Fig. 8. The overall

TABLE 5. Hydraulic β Factor and Soil Characteristic for Experimental Sites

Experimental site	β ($mm^{1/2}$)	Soil type
Imperial Valley, Calif.	4.3	Very fine sandy loam
Ventura, Calif.	3.8	Sandy loam
Oristano, Italy	1.9	Clayey sandy loam

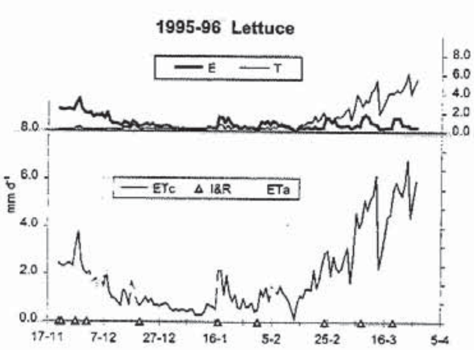

FIG. 5. Modeled Crop Evapotranspiration ET_c, Transpiration T, Evaporation E, Irrigation and Rainfall Events (I&R), and Measured Actual Crop Evapotranspiration ET_a for 1995–1996 Lettuce Crop

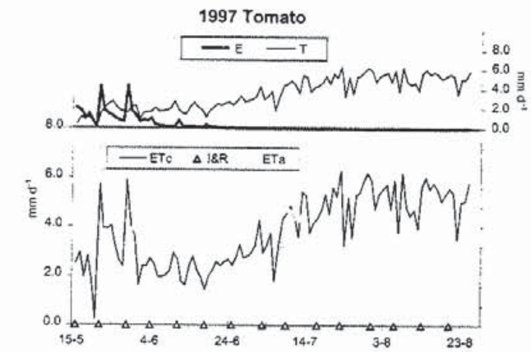

FIG. 6. Modeled Crop Evapotranspiration ET_c, Transpiration T, Evaporation E, Irrigation and Rainfall Events (I&R), and Measured Actual Crop Evapotranspiration ET_a for 1997 Tomato Crop

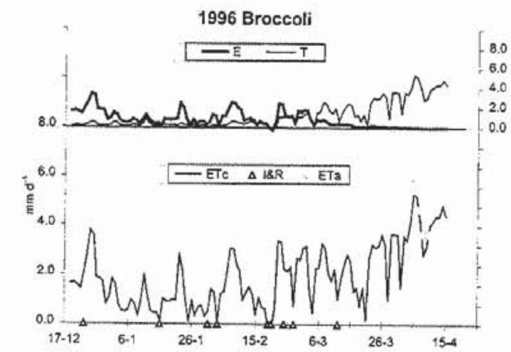

FIG. 7. Modeled Crop Evapotranspiration ET_c, Transpiration T, Evaporation E, Irrigation and Rainfall Events (I&R), and Measured Actual Crop Evapotranspiration ET_a for 1996 Broccoli Crop

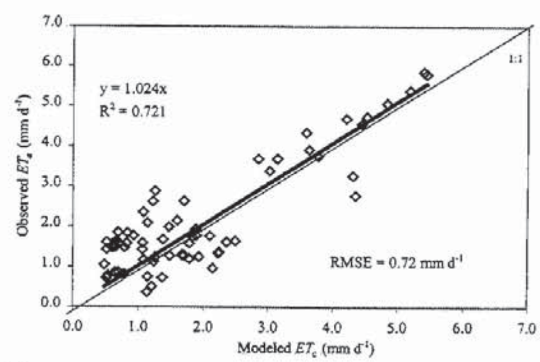

FIG. 8. Observed Crop Evapotranspiration ET_a versus Modeled Crop Evapotranspiration ET_c Using Data from All Five Field Experiments

RMSE is equal to 0.72 mm day^{-1} with less accurate results during periods with low ET_0. All of the data with $ET_c < 3$ mm day^{-1} occurred in the wintertime lettuce experiment. Comparing daily evapotranspiration data calculated with the Food and Agricultural Organization of the United States (FAO) K_c model (Doorenbos and Pruitt 1977) with the measured ET_a shows a greater data scattering ($R^2 = 0.61$) and RMSE = 0.90 mm day^{-1}.

CONCLUSIONS

An evapotranspiration model for vegetable crops is reported. The model estimates evaporation from bare soil and transpiration from the vegetation. Model results show good agreement with ET_a measurements taken on three different crops in five experiments. The model uses daily ET_0 as the single input parameter. This makes it suitable for use by farmers, optimizing irrigation schedules for horticultural crops. This could potentially lead to more efficient water usage and reduced groundwater contamination.

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NOTATION

The following symbols are used in this paper:

a, b = regression parameters;
C_i = ground cover percentage on *i*th day (%);
C_n = maximum ground cover percentage for season (%);
CE = cumulative bare soil evaporation (mm);
$E, E_s, E1, E2$ = soil evaporation, from bare soil, general, in stage one, and in stage two (mm);
ET_a = actual evapotranspiration (mm);
ET_c = crop evapotranspiration (mm);
ET_x = maximum possible ET_c (mm);
ET_0 = reference evapotranspiration (mm);
ET_{0n} = cumulative ET_0 at end of season (mm);
G = soil heat flux density (W m^{-2});
H = sensible heat flux density (W m^{-2});
K_c = crop coefficient;
K_s = wet soil crop coefficient;
N_i = normalized cumulative reference evapotranspiration;
P_i = normalized ground cover percentage on *i*th day;
R_i = percentage radiation interception by canopy on *i*th day (%);
R_n = net radiation (W m^{-2});
T = transpiration (mm);
W = percentage irrigation wetted area (%); and
β = soil hydraulic factor ($mm^{0.5}$).