7.13 A MODIFIED SEBAL MODEL FOR SPATIALLY ESTIMATING PECAN CONSUMPTIVE WATER USE FOR LAS CRUCES, NEW MEXICO

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1. ABSTRACT

Pecan is an important cash crop in arid southern New Mexico, west Texas and Arizona. However, water use by pecan trees is greater than that of most row crops, except alfalfa. Estimating pecan water use is an important research objective in these arid areas to guide water management. Unfortunately, the point measurement of water use in one pecan orchard cannot provide a complete and accurate estimate for all the orchards in a large area such as a county or state. Numerous point measurements will also be costly and unpractical. A modified SEBAL (Surface Energy Balance Algorithm for Land) spatially estimates pecan water use for Las Cruces New Mexico from available ASTER satellite data. The modified SEBAL model estimates evapotranspiration (ET) in terms of energy balance equations. Using the surface temperature and reflectance data from ASTER satellite and weather data from local weather station, the model calculates net radiation, soil and sensible heat flux, and evapotranspiration. Compared with point ET measurements of pecan and alfalfa from 2002 to 2004, the modified SEBAL provides accurate information. The average relative error was 11%, and the average absolute error was 0.47 mm/day. This model provides guidelines for farmers and the government on how to evaluate current water-use schemes.

2. INTRODUCTION

Pecan is an important cash crop in arid southern New Mexico, west Texas and Arizona, but water use by pecan trees is greater than that of most row crops, except alfalfa. Pecan has an annual evapotranspiration (ET) of about 1.4m via 2m irrigation a year (Miller, et al., 2005). Estimating pecan water use is an important research objective in arid areas. Ground measurements are labor- and time consuming and cannot obtain accurate spatial ET estimation.

Different methods have been developed to estimate spatial evapotranspiration based on satellite data (Caurault, et al., 2003). There are two main methods: direct and indirect. Direct methods mainly use thermal infrared data (TIR) and the energy budget equation. Indirect methods use the assimilation procedure and Soil-Atmosphere Transfer models. These methods use different wavelength data and obtain ground surface characteristics such as albedo, emmissivity, and leaf area index (Caurault, et al., 2003).

Direct methods

The Direct Simplified Methods are often used to estimate ET , which are empirical methods. The methods assume the daily ET linearly relates to the cumulative temperature difference ($T_s - T_a$) (surface temperature minus the air temperature) (Caurault, et al., 2003). On a local scale, accuracy could be reached at 85-90% (Steinmetz, et al., 1989). But if the method is used for regional scale, the accuracy will be around 70-80% because the input parameter (air temperature) must be interplated from local measurement.

SEBAL is one of the residual methods of energy budget, developed by (Bastiaanssen, et al., 1998). It combines empirical and physical parameterization. The inputs include local weather data (mainly wind speed) and satellite data (radiance). From the input data, the Rn (net solar radiation), $NDVI$, albedo, roughness length, and G (soil heat flux) are calculated. The sensible heat flux is calculated by contrasting two points (wet, well-irrigated vegetation and dry ground). Then, the ET is calculated as the residual of the energy budget (Bastiaanssen, et al., 1998). The accuracy can be 85% in daily basis and 95% in seasonal basis (Bastiaanssen, et al., 2005). Based on the contrast of wet and dry areas, similar models like SEBI, -S-SEBI and SEBS were developed (Menenti and Choudhury 1993; Roerrink, et al., 2000; Su 2002).

In the residual models, a two-source model (Kustas and Norman 2000) divides the energy calculation into two parts. One is the canopy, and the other is the soil. The model estimates ET with an accuracy of about 90% (Kustas and Norman 2000). However, the model is more complicated than SEBAL and accurate surface temperature data are needed.

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Indirect methods

Indirect methods deal with soil and plant energy exchange with the atmosphere with a fine time step of 1 s to 1 hr (Caurault, et al., 2003). Indirect methods accurately describe crop functioning, and can allow access to the intermediate variables such as soil moisture and LAI (leaf area index), which are related to the physiological and hydraulic processes that can be linked to other meteorological and hydrologic models (Caurault, et al., 2003).

Model comparison and point ET measurement

Most of the models use TIR data to obtain the surface temperature and need accurate temperature data. SEBAL avoids the problem (to input accurate surface data) by using the temperature difference between air and ground for each pixel which is scaled by surface temperature in contrast with dry and wet spot values. Thus, SEBAL is more attractive for operational applications (Caurault, et al., 2003).

OPEC and Li-Cor eddy correlation systems are often used to measure plant ET (Sammis, et al., 2004; Miller, et al., 2005). An OPEC system is much cheaper than a Li-Cor system, but an OPEC system needs to be calibrated by a Li-Cor system to obtain accurate data (Miller, et al., 2005). The Li-Cor eddy correlation system uses high frequency (e.g. 10 Hz) to measure vapor flux and ET (Miller, et al., 2005).

3. MATERIALS AND METHODS

Model

A Modified SEBAL model written in c++ program language was developed and validated. The model can estimate ET in 90 m × 90 m resolution using ASTER and local weather data. ASTER data was obtained from NASA Earth Observing System Data Gateway (http://redhook.gsfc.nasa.gov/~imswww/pub/imswelcome/). The model general flowchart is shown in Figure 1. This model inputs ASTER satellite data (ground surface reflectance and temperature) and local weather data (solar radiation and wind speed). Then, it calculates $NDVI$, the soil heat flux (G) and sensible heat (H) flux. Finally, it outputs the spatial ET (mm/day) according to the energy budget equation.

Inputs

The inputs include wind speed, humidity and solar radiation data at the local weather station and satellite data products from ASTER including ground surface reflectance and temperature. The reflectance has a resolution of 15 m × 15 m for the bands 1 to 3 (Visible and Near-infrared bands) and 30 m × 30 m for the bands 4 to 9 (Shortwave Infrared bands). The temperature data has a resolution 90 m × 90 m. The reflectance data were averaged over 90 m × 90 m to fit the temperature data resolution. This model does not calculate solar radiation, ground surface temperature and reflectances. Instead, the data products are obtained from ASTER website directly. This simplified the model complexity, which reduce the program work and time, and the data products quality is guaranteed.

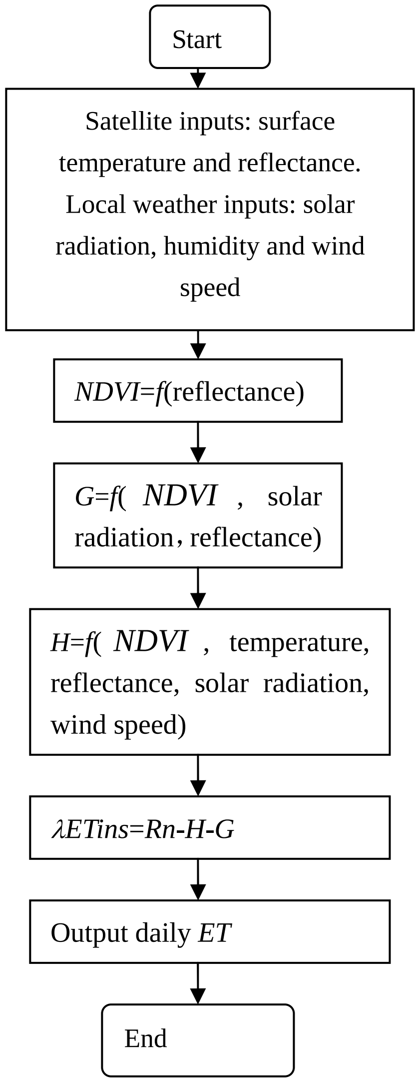

Figure 1. The general flowchart of the modified SEBAL model.

Outputs

The spatial ET (mm/day) is the output from the model. The resolution is 90 m × 90 m.

Theory

The method uses the energy budget equation to calculate each pixel $\lambda ETins$ (instant latent heat loss) at the time of the satellite overflight.

$$\lambda ETins = Rn - G - H \quad (1)$$

where:

$\lambda ETins$: the instant latent heat loss (w/m^2), which is calculated as a residual of the energy budget, λ is the heat loss when a gram of water evaporates, $ETins$ is the rate of evapotranspiration of water at the time of the satellite overflight,

Rn is net solar radiation (w/m^2),

G is soil heat flux into the soil (w/m^2),

H is sensible heat into the air (w/m^2),

Rn is calculated according to the local solar radiation data (Walter, et al., 2002).

$$Rn = Rns - Rnl \quad (2)$$

where:

Rns is net short-wave radiation (w/m^2),

Rnl is net long-wave radiation (w/m^2).

$$Rns = (1-\alpha)Rs \quad (3)$$

where:

α is surface albedo,

Rs is incoming solar radiation measured at the local weather station (w/m^2).

α is calculated by the equation in Liang (2000) from ASTER surface reflectance data.

$$\alpha = 0.484\alpha_1 + 0.335\alpha_3 - 0.324\alpha_5 + 0.551\alpha_6 + 0.305\alpha_8 - 0.367\alpha_9 - 0.0015 \quad (4)$$

α_i is the reflectance for ASTER data band i.

According to (Walter, et al., 2002),

$$Rnl = 277.8\sigma T_s^4 (0.34 - 0.14\sqrt{e_a}) \quad (5)$$

where:

T_s =mean absolute surface temperature (K), which is obtained from the satellite data,

σ =Stefan-Boltzmann constant (2.042x10^{-10} MJ/K^4/m^2 /hr).

e_a is the actual vapor pressure (kPa),

$$e_a = \frac{RH}{100} e_s(T_a) \quad (6)$$

where $e_s(T_a)$ is saturation vapor pressure (kPa), T_a is air temperature (^{o}C).

$$e_s(T_a) = 0.6108\exp(\frac{17.27T_a}{T_a + 237.3}) \quad (7)$$

$$T_a = T_s - dT - 273 \quad (8)$$

dT is the difference between surface temperature and air temperature (K, equation 16).

$$G = G/Rn \times Rn \quad (9)$$

According to (Bastiaanssen, et al., 1998),

$$G/Rn = Ts(0.0032 + 0.0062\alpha)(1 - NDVI^4) \quad (10)$$

where T_s is the surface temperature, α is the albedo, $NDVI$ is the normalized difference vegetation index.

$NDVI$ is calculated as the following:

$$NDVI = \frac{\alpha_3 - \alpha_2}{\alpha_3 + \alpha_2} \quad (11)$$

where α_3 and α_2 are the reflectance data of bands 3 and 2 respectively.

For the sensible heat flux calculation, two pixels are chosen in the satellite data. One pixel is a wet pixel that is a well-irrigated crop surface with full cover and the surface temperature (T_s) close to air temperature. The second pixel is a dry bare agricultural field where $\lambda ETins$ is assumed to be 0. The two pixels tie the calculations for all other pixels between these two points.

At the dry pixel, assume $\lambda ETins$ =0, then according to equation 1,

$$H = Rn - G \quad (12)$$

$$H = \frac{\rho \times c_p \times dT}{r_{ah}} \quad (13)$$

Where ρ is the air density (mol/m^3), c_p is the specific heat of air (29.3 J/mol/ ^{o}C), dT is the near surface temperature difference (K), r_{ah} is the aerodynamic resistance to heat transport (s/m), where

$$r_{ah} = \frac{\ln(\frac{z_2}{z_1})}{u^* k} \quad (14)$$

z_1 is a height just above the zero displacement distance height of plant canopy set to 0.1 m for each pixel, and z_2 is the reference height just above the plant canopy set to 2 m for each pixel, u^* is the friction velocity (m/s), and k is the von Karman constant (0.4).

$$u^* = \frac{u(z)k}{\ln(\frac{z-d}{z_m})} \quad (15)$$

where $u(z)$ is the wind speed at height of *z*, *d* is the zero displacement height (m, *d*=0.65*h*), *h* is the plant height (m), and z_m is the roughness length (m, z_m =0.1*h*)(Campbell and Norman 1998). According to equations 12-15 and the input data, $dTdry$, dT at the dry spot can be calculated. At the wet spot, assume H =0 and $dTwet$ =0 (dT at the wet spot). Then according to the surface temperature at the dry and wet spots ($Tsdry$ and $Tswet$, K), we can get one linear equation for each pixel,

$$dT = \left(\frac{dTdry - dTwet}{Tsdry - Tswet}\right) \times Ts - \left(\frac{dTdry - dTwet}{Tsdry - Tswet}\right) \times Tswet \quad (16)$$

Then, according to the equation, the H at each pixel can be calculated according to equations 13-15. We assumed at 200 m the wind speed is the same for each pixel and the wind speed at 200 m is calculated for the weather station first, and then u^* can be solved for each pixel (equation 15). The parameter d in equation 15 is set to 0 which is negligible when z =200 m. The z_m for each pixel is calculated by a regression equation according to the pixel $NDVI$ value. The equation is obtained by three pair of known values of z_m and $NDVI$. For example if we know that pecan has z_m =1.2 m and $NDVI$ =0.57, for alfalfa z_m =0.07 m and $NDVI$ =0.42, and bare agricultural field z_m =0.003 m and $NDVI$ =0.18, then we can obtain a regression equation for z_m (Figure 2).

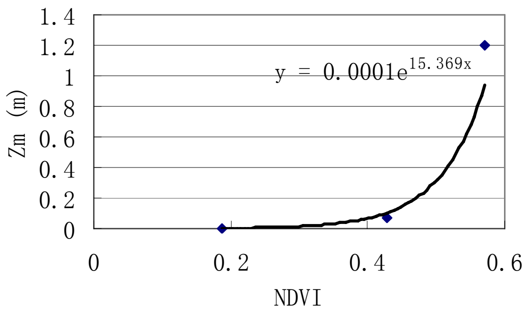

Figure 2. One example regression equation for z_m from $NDVI$.

Because atmospheric stability may have effects on H, the atmospheric correction is conducted (Figure 3). First the u^* and wind speed at 200 m at the local weather station are calculated. Then the z_m, u^* and dT for each pixel are computed. Then the r_{ah} and H without the atmospheric correction are obtained.

For atmospheric correction, the stability parameter, Obukhove length, L (m) is calculated. Then using the stability parameter, u^*, r_{ah}, and H are corrected. Then an iteration is conducted for L, u^*, r_{ah}, and H calculation until H does not change more than 10%. The correction equations are as the follows (Campbell and Norman 1998; Stull 2001).

$$L = -\frac{{u^*}^3 T_s}{kgH} \quad (17)$$

When $L < 0$, H is positive and heat is transferred from ground surface to air, under unstable condition; when $L > 0$, H is negative and heat is transferred from air to ground surface, under stable condition; when $L = 0$, no heat flux occurs, and is under neutral condition. Because the satellite overflight occurred at local noon time, the atmosphere should have been untable. Thus, when $L > 0$ (stable) occurred, we forced $L = 0$ (neutral).

The momentum correction term is

$$\varphi(\frac{z}{L}) = 0 \quad \text{for } L = 0 \qquad (18)$$

$$\varphi(\frac{z}{L}) = -2\ln(\frac{1+\beta}{2}) - \ln(\frac{1+\beta^2}{2}) + 2\tan^{-1}(\beta) - \frac{\pi}{2} \quad \text{for } L < 0 \qquad (19)$$

$$\beta = [1 - 15(z-d)/L]^{0.25} \qquad (20)$$

$$u* = \frac{ku(z)}{\left[\ln(\frac{z-d}{z_m}) + \varphi(\frac{z}{L})\right]} \qquad (21)$$

z =200 m and then d is negligible (d =0).

The correction term for the heat transfer is

$$\psi(z) = 2\ln(\frac{1+\beta_z^2}{2}) \quad \text{for } L < 0 \qquad (22)$$

$$\psi(z) = 0 \quad \text{for } L = 0 \qquad (23)$$

$$r_{ah} = \frac{\ln(\frac{z_2}{z_1}) - \psi(z_2) + \psi(z_1)}{u^* k} \qquad (24)$$

After H is corrected by the atmospheric effects, $\lambda ETins$ for each pixel is calculated using equation 1. The daily ET ($ETdaily$, mm/day) is calculated as:

$$ETdaily = \frac{\lambda ETins}{\lambda ETrins} ETrdaily \qquad (25)$$

where $ETrdaily$ is the daily ET for well-irrigated alfalfa. The $ETrdaily$ can be obtained by the FAO Penman-Monteith equation (weather.nmsu.edu). The $\lambda ETrins$ (w/m^2) is the instant λET for well-irrigated alfalfa field calculated from equations 1-9 (α =0.23, G/Rn =0.04, and $Ts = Tswet$).

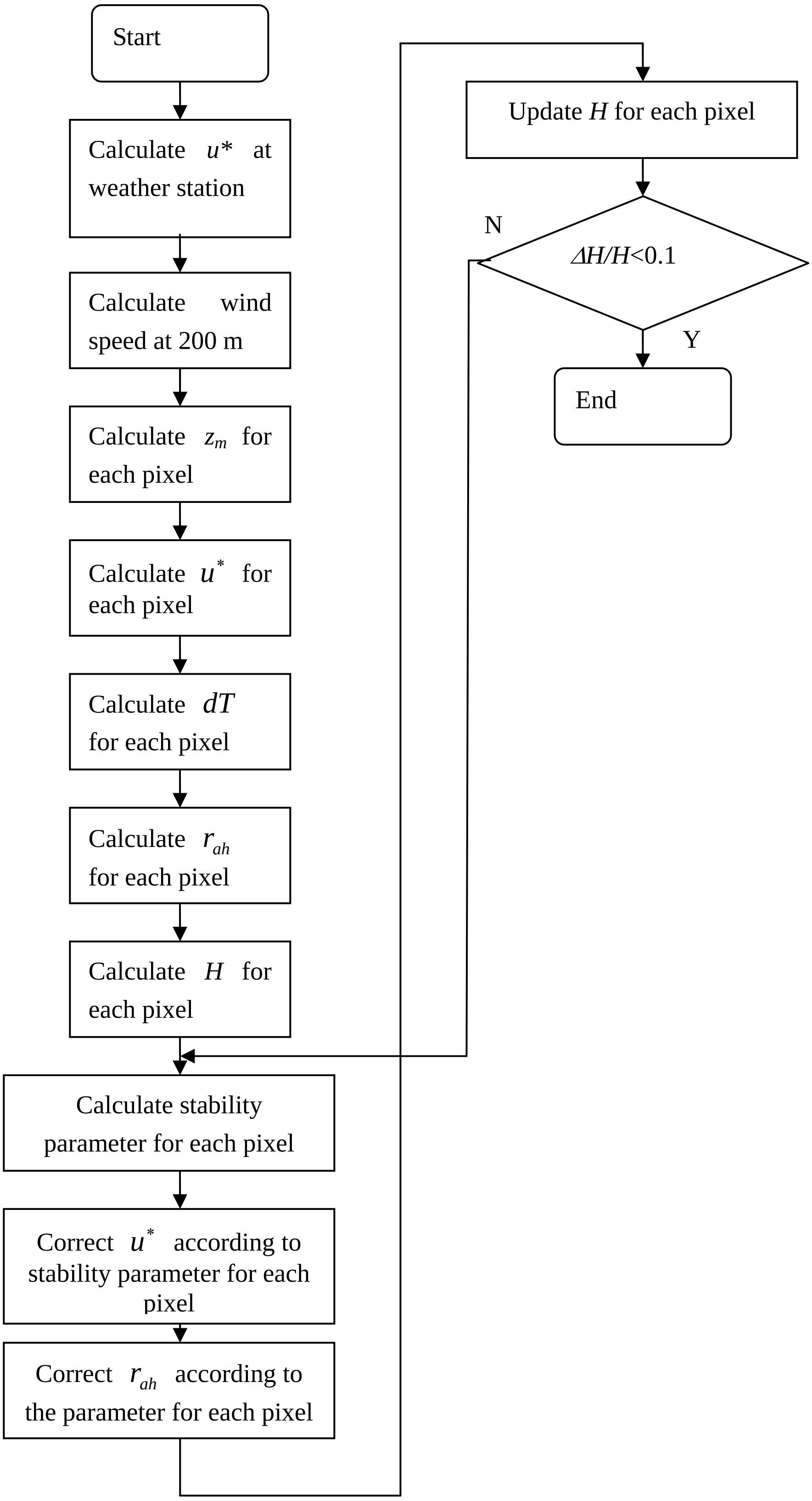

Figure 3. Atmospheric correction for H.

The site and ET measurements

The Las Cruces pecan crop area is in southern New Mexico. Figure 4 and 6 show the Las Cruces pecan crop area. The most of blue areas in Figure 6 are pecan orchards.

A 5 ha pecan orchard (green circled in Figure 4) was planted in 1970 at 10.0 m × 10.0 m tree spacing. A 5 ha alfalfa field is located 2.5 km southeast of the pecan orchard (red circled). From 2002 to 2004, in the orchard and the field, Li-Core eddy correlation systems were set up to measure ET at above the canopies (Figure 5) The daily total ET was processed from the measurements. The processing method is the same as in (Miller, et al., 2005). The daily ET was compared with the model outputs.

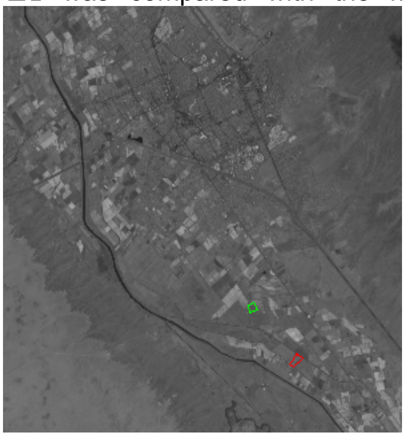

Figure 4. Las Cruces crop area and the measurement sites: Pecan orchard (green) and alfalfa field (red).

Figure 5. The pecan orchard ET measurement. The Li-Core eddy correlation system is on the top of the 16 m tower.

ET Observation and simulation Comparison

The measured and simulated ET is compared. The relative error is calculated as:

$$RelativeError = \frac{|\,simulation - observation\,|}{observation} \qquad (26)$$

The absolute error is calculated as (mm/day):

$$AbsoluteError = |\,simulation - observation\,| \qquad (27)$$

The average of the relative error and the absolute error was also calculated, respectively. To see if a day was water-stressed in alfalfa field, the non-stressed ETr (alfalfa ET, mm/day) calculated by FAO Penman-Monteith equation was compared with the corresponding observation. The ETr was obtained from New Mexico State Climate Center (Weather.nmsu.edu). The pecan orchard was always well-irrigated and nonstressed.

4. RESULTS AND DISCUSSION

One sample ET map for Las Cruces is shown in Figure 6 (September 4, 2002). The pecan crop area obtained high ET values (blue areas). The desert area had very low ET (red areas).

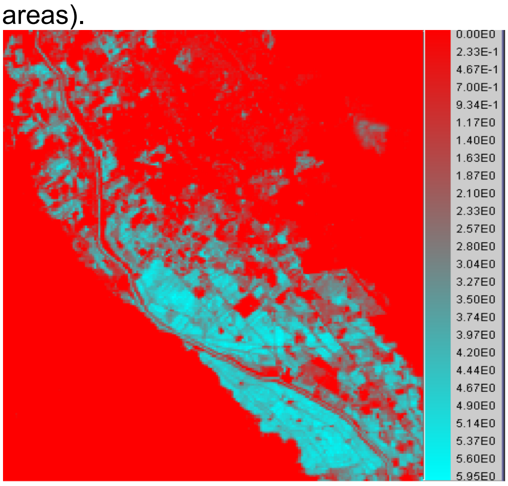

Figure 6. The simulated ET in the Las Cruces area on September 4, 2004. Resolution: 90 by 90 m. The false color was added using HDFView2.1 (http://hdf.ncsa.uiuc.edu/hdf-java-html/hdfview/)

The ET from the model for alfalfa and pecan fields is accurate (Table 1, 2, Figure 7). The relative error for alfalfa was 2%, 6%, and 5% respectively, for the three satellite overflight days. The absolute errors were within 0.3 mm/day, i.e. 0.2, 0.3, and 0.2 mm/day, respectively. The alfalfa field was stressed on September 4, 2002, and May 18, 2003 (ETr compared with the observation).

The comparison of ET estimation for the pecan orchard is shown in Figure 7 and Table 2. The relative error was within 24%, and the absolute error was within 1 mm/day.

Table 1. The alfalfa ET of simulation vs. observation

Date	*Ob*	*Si*	*ETr*	*RE*	*AE*
5/18/03	4.0	3.8	7.1	5%	0.20
9/4/02	4.7	4.4	5.7	6%	0.30
6/17/02	8.8	8.6	8.2	2%	0.20

Ob: ET observation (mm/day), *Si*: ET simulation (mm/day), ETr : Well-irrigated alfalfa ET (mm/day), *RE*: Relative error, *AE*: Absolute error (mm/day).

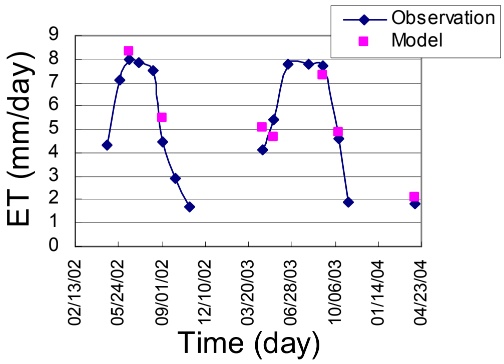

Figure 7. The pecan ET of simulation vs. observation.

Table 2. The pecan ET of simulation vs. observation

Date	*Ob*	*Si*	*RE*	*AE*
4/9/04	1.8	2.1	17%	0.30
4/23/03	4.1	5.1	24%	1.00
9/4/02	4.5	5.5	22%	1.00
10/16/03	4.6	4.9	7%	0.30
5/18/03	5.4	4.7	13%	0.70
9/7/03	7.7	7.3	5%	0.40
6/17/02	8.0	8.3	4%	0.30

Ob: ET observation (mm/day), *Si*: ET simulation (mm/day), *RE*: Relative error, *AE*: Absolute error (mm/day).

For both the alfalfa and pecan ET simulation, the average relative error was 11% with a standard deviation of 8%. The average absolute error was 0.47 mm/day with a standard deviation of 0.31 mm/day.

The model can calculate ET under both stressed and nonstressed conditions accurately. The accuracy is comparable with other studies. For example, using SEBAL model, the daily ET accuracy can be 85% (Bastiaanssen, et al., 2005).

5. CONCLUSION

The modified SEBAL is capable calculating the spatial pecan daily water use (ET) with resolution of 90 m × 90 m. The simulated ET is accurate compared with measurement under both stressed and nonstressed conditions. The average relative error was 11%, and the average absolute error was 0.47 mm/day. This model provides guidelines for farmers and the government on how to evaluate current water-use schemes.

6. ACKNOWLEDGMENTS

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