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SOIL TEMPERATURE UNDER A DORMANT BERMUDAGRASS MULCH: SIMULATION AND MEASUREMENT

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ABSTRACT. *The ENergy and WATer BALance (ENWATBAL) model is a mechanistic, numerical model that simulates soil water and temperature profiles, evaporation from soil, and transpiration from crops, but it does not simulate the effects of a mulch layer. Surface vegetative mulches are becoming more common, especially in reduced-tillage systems, limiting the model's applicability. Our objective was to modify ENWATBAL to enable physically based simulation of the effects of a dense mulch. As a preliminary evaluation of the model, soil temperatures simulated with the modified model were compared with those measured at Watkinsville, Georgia, in Cecil sandy loam (clayey, kaolinitic, thermic, Typic Kanhapludult) under a dense, thatchy layer of dormant bermudagrass (Cynodon dactylon, [L.] Pers.) that acted as a mulch during the simulation period. Measured daily soil temperature amplitudes at 0.04 m depth were about 2.5°C during an 8-day period in December 1995. Simulated amplitudes were 12°C with the original ENWATBAL model (configured for a bare soil) and 3.5°C with the mulch-enhanced model. The root mean square error between hourly measured and simulated soil temperatures was 4.1°C using the original ENWATBAL model and 1.1°C using the mulch-enhanced model. Measured soil temperatures lagged behind those simulated, indicating that conduction may be an important process of heat transfer through the mulch. Two solution methods were tested: an iterative solution for mulch and soil surface temperatures implicit in the energy balance equations, and a linearized explicit solution of the energy balances. The latter method was 50 times faster than the iterative method without compromising accuracy; the largest linearization error was only 0.01°C. The capability to simulate mulch effects increases the scope of problems where ENWATBAL is applicable.*

Keywords. *Bermudagrass, Energy balance, ENWATBAL, Mulch, Soil temperature.*

Soil temperature affects many biological, chemical, and physical processes. Management practices such as mulching, soil wetting, and ridging (microtopography and ridge orientation) can have large impacts on soil temperature. Mulch can be thought of in a rather broad sense and may include residue of a harvested crop, residue of chemically killed wheat, a layer of wood chips or pine straw, or a dormant perennial sod. Managing soil temperature offers the potential to grow crops that require a temperature regime different from the unmanaged environment. For example, Tindall et al. (1991) found that straw mulches improved tomato yields in the high-temperature environment of Georgia. Soil temperature management can aid in controlling diseases, such as aflatoxin development in peanut (Hill et al., 1983). Soil temperature is also critical in biological and chemical processes that control nutrient cycling.

Novak et al. (2000a, 2000b) showed that convection was the principal mechanism of heat and water transfer within a straw mulch. They demonstrated that this transport was accomplished by large convective eddies. There are a number of models that simulate soil-mulch-atmosphere systems (Bristow et al., 1986; Bristow, 1988; Bussiere and Cellier, 1994; Ross et al., 1985). Bristow et al. (1986) treated the soil-mulch-atmosphere system as a continuum. In their model, driving forces are gradients in temperature, water potential, and water vapor density. Finite difference nodes are separated from each other by conductance elements throughout the continuum. Some models have the ability to simulate systems in which a mulch partially covers the soil (Chung and Horton, 1987; Hares and Novak, 1992; Bristow and Horton, 1996; Farahani and Ahuja, 1996).

The ENWATBAL (ENergy and WATer BALance) model simulates a soil-crop-atmosphere system. It is a mechanistic, numerical model capable of simulating soil temperatures. It simulates soil water and temperature profiles simultaneously with soil water evaporation and crop transpiration. Although this model is generally applicable, it has been primarily tested for evaluating crop and water management systems that conserve water in the High Plains area in Texas, with special emphasis on partitioning of energy to soil water evaporation and crop transpiration (Van Bavel and Lascano, 1993).

Evett and Lascano (1993) made ENWATBAL accessible to personal computers by converting it from the Continuous System Modeling Program (CSMP) simulation language to the BASIC language. The new model was named ENWATBAL.BAS, and it introduced new code to simulate transpiration more accurately, allow soil albedo to vary with surface water content, allow soil hydraulic properties to differ among soil horizons, allow hourly weather data input, as well as oth-

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er improvements. Most studies since 1993 have used the BASIC version. Lascano et al. (1994) studied soil and water evaporation from strip-tilled cotton using an extension of this version. Evett et al. (1994, 1995b) used ENWATBAL.BAS to simulate the energy and water balance of winter wheat at Bushland, Texas, and showed that evapotranspiration (ET) estimates compared well with those made using crop coefficients and reference ET values measured at Bushland. They also estimated the extra evaporative loss of irrigation water from surface vs. subsurface drip irrigated corn using the model (Evett et al., 1995a). Schomberg et al. (1996) used ENWATBAL.BAS to simulate the near-surface soil water content that affects decomposition rates of sparse crop residues in their study of alfalfa, sorghum, and wheat residues.

Lascano and Baumhardt (1996) modified ENWATBAL.BAS to simulate a mulch layer. However, they indicated that their effort was a “first approximation” to their particular cotton-wheat-stubble system and that “whenever possible, a mechanistic approach should be used.” The objectives of this study were to add to ENWATBAL.BAS the capability to mechanistically simulate the effects of a dense mulch, and to test its performance by comparing simulated with measured soil temperatures under a dormant bermudagrass sod. The existing model without mulch will be referred to as ENWATBAL.BAS and the modified model as EWBM (Energy and Water Balance including a dense Mulch).

DESCRIPTION OF ENWATBAL.BAS

The most complete documentation of ENWATBAL is given by Van Bavel and Lascano (1993). The ENWATBAL.BAS model is documented in the BASIC source code listing available at www.cprl.ars.usda.gov/programs/ and in other documents available at that site. The following description is not meant to be exhaustive, but rather to emphasize aspects of ENWATBAL.BAS that were modified when introducing a mulch into the model.

ENWATBAL.BAS is a “big leaf” model that treats the plant canopy as one layer with only one value for canopy (or crop) temperature, as opposed to a vertical temperature profile in the canopy. Up to nine soil horizons with different physical properties can be defined. One horizon consists of one or more layers (table 1), which are defined because of the finite-difference character of the one-dimensional, numerical model. Layers at the soil surface are typically very thin. The top layer should not be more than 2 mm if a correct partitioning of soil water evaporation and crop transpiration is desired. Layers at horizon interfaces should also be thinner than other layers (Evett and Lascano, 1993).

Temperatures (soil surface and crop) that satisfy the energy balance equations are found at every time step through an iterative solution of the respective sets of equations in which surface temperatures are implicit. The time step in ENWATBAL.BAS is variable. The user can specify the minimum and maximum time step. Typical values are 1 s for the minimum and 30 s for the maximum time step. This short time step is needed for the iterative solutions to converge. Inputs include initial conditions (table 1), weather data at daily or shorter time intervals (table 2), crop rooting parameters, leaf area index, and hydraulic properties (water retention data and hydraulic conductivity) for each soil horizon.

Table 1. Sixteen soil layers used in the simulations covering six physical soil horizons, and initial soil conditions at the beginning of day 356, 1995, Watkinsville, Georgia.

Layer Thickness (m)	Cumulative Layer Thickness (m)	Layer Midpoint[a] (m)	Horizon	Initial Soil Water Content (m^3 m^{-3})	Initial Soil Temp. (°C)
0.001	0.001	0.0005	Ap	0.174	2.2
0.024	0.025	0.013	Ap	0.174	2.9
0.030	0.055	0.040	Ap	0.174	3.3
0.030	0.085	0.070	Ap	0.142	4.0
0.070	0.155	0.120	Ap	0.159	4.7
0.025	0.180	0.168	Ap	0.159	5.2
0.050	0.230	0.205	BA	0.184	5.8
0.040	0.270	0.250	BA	0.184	6.5
0.060	0.330	0.300	BA	0.184	7.1
0.070	0.400	0.365	Bt1	0.290	7.6
0.140	0.540	0.470	Bt1	0.290	8.7
0.080	0.620	0.580	Bt2	0.362	9.4
0.080	0.700	0.660	Bt2	0.362	10.1
0.360	1.060	0.880	BC1	0.354	10.8
0.170	1.230	1.145	BC1	0.354	12.1
0.540	1.770	1.500	BC2	0.381	13.1

[a] Distance from the soil surface to the layer midpoint.

Table 2. Daily weather data, Watkinsville, Georgia, December 1995.

Day of Year	Temperature (°C)		Solar Irradiance (MJ m^{-2} day^{-1})	Wind Speed (m s^{-1})	Relative Humidity (%)
	Max.	Min.			
354	8.1	-2.5	12.5	4.3	60.4
355	6.9	-4.3	10.4	2.9	56.2
356	3.2	-7.0	6.5	1.6	71.6
357	5.3	-6.9	12.0	2.9	67.2
358	3.3	-5.2	12.5	3.9	55.6
359	6.8	-5.6	12.0	4.1	66.0
360	5.6	-6.2	12.5	2.9	54.1
361	6.9	-3.2	10.3	2.9	63.2
362	6.0	-6.0	12.2	1.1	64.4
363	9.3	-8.2	12.6	0.8	63.7
364	10.6	-5.4	7.2	1.4	73.4

Calculation of soil thermal properties is based on work by De Vries (1963). Soil volumetric heat capacity is found from the heat capacities of the different soil constituents. The contribution of air in the soil to heat capacity is neglected. Soil thermal conductivity is calculated from conductivities of three phases (solid, liquid, and gaseous) or alternatively, as a function of soil water content. Thermal conductivity of water vapor is a function of temperature and contributes to overall thermal conductivity. Heat transport in the soil is assumed to be only by conduction (diffusion) and not by convection (transport of heat along with moving water). At the lower boundary of the soil profile, temperature is set to a constant value equal to the initial soil temperature at that depth (table 1).

Solar irradiance is partitioned over canopy (big leaf) and soil surface. Partitioning is a function of leaf area index (LAI) and is derived from work by Chen (1984). Net radiation at the soil surface is found from solar irradiance at the soil surface, soil albedo, and soil longwave radiation balance. The soil surface energy balance (net radiation, latent heat flux, sensible heat flux, and soil heat flux at the surface) is solved iteratively for the implicit soil surface temperature. Similarly, net radiation for the canopy is found from solar irradiance at the plant canopy, canopy albedo, and canopy longwave radiation balance. The canopy energy balance is solved iteratively for the implicit canopy (crop) temperature.

METHODS

The starting point for EWBM was ENWATBAL.BAS without the modifications by Lascano and Baumhardt (1996). A mulch layer was introduced in ENWATBAL.BAS as a "big leaf," much like the crop canopy in ENWATBAL.BAS. Thus, it has one mulch temperature, as opposed to a vertical temperature profile in the mulch. A mulch resistance to sensible and latent heat flux was conceived in addition to the aerodynamic resistance in ENWATBAL.BAS (fig. 1). It was assumed that a dense mulch, such as a dormant bermudagrass sod, is opaque to radiation.

There are two energy balances: one at the top of the dense mulch layer and one at the soil surface (fig. 1). The energy balance of the mulch is:

$$R_{nm} + H_{ms} + H_{ma} + LE_{mulch} = 0 \qquad (1)$$

where R_{nm} is net radiation of the mulch, H_{ms} is sensible heat flux between the mulch and the soil surface, H_{ma} is sensible heat flux between the mulch and the air, and LE_{mulch} is evaporation from the mulch (all in W m^{-2}). Fluxes toward the mulch surface are positive.

Net radiation of the mulch can be calculated from:

$$R_{nm} = ABSM \times R_g - R_{mulch} + R_{sky} \qquad (2)$$

where ABSM is the fraction of shortwave radiation absorbed by the mulch, R_g is shortwave irradiance, R_{mulch} is longwave (thermal) radiation emitted by the mulch, and R_{sky} is longwave (thermal) radiation emitted by the sky (all in W m^{-2}). Global irradiance was either reflected or absorbed by the dense, opaque mulch layer. The albedo of the dormant bermudagrass was estimated as 0.25 (D. Stark, personal communication, 1998). Then ABSM = 1 - 0.25 = 0.75.

$$R_{mulch} = \sigma (T_{mulch} + 273.16)^4 \qquad (3)$$

where σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), and T_{mulch} is mulch temperature (°C). Mulch emissivity is assumed to be equal to 1.0, just as the soil surface and crop canopy emissivities in ENWATBAL.BAS. In reality, these emissivities are slightly less than 1.0. Errors caused by this assumption are expected to be minor since ENWATBAL.BAS has been tested successfully.

In ENWATBAL.BAS, there are sensible heat fluxes between soil and air and between crop and air, but not between soil and crop. For EWBM, sensible heat fluxes between all the components (air, mulch, and soil) were introduced, including sensible heat flux between mulch and soil. The latter may be very important for a dense mulch where no shortwave irradiance reaches the soil surface to warm the soil directly. All of this irradiance is intercepted by the mulch, warming it considerably on a sunny day. The soil is then warmed by the sensible heat flux from the mulch to the soil, expressed as:

$$H_{ms} = \rho c_p \frac{T_{soil} - T_{mulch}}{r_m} \qquad (4)$$

where ρ is air density (kg m^{-3}), c_p is specific heat of air (J kg^{-1} $°C^{-1}$), T_{soil} is soil surface temperature (°C), and r_m is mulch resistance (s m^{-1}).

Van Donk and Tollner (2000) measured r_m in the laboratory, using dormant bermudagrass sods that were obtained from near the site where the soil temperatures were measured that were used for model testing. Their empirical relationship is used in EWBM:

$$r_m = \rho c_p (-0.0203u + 0.3823) \qquad (5)$$

where u is air velocity (m s^{-1}) measured 0.45 m above the mulch. Thus, r_m decreases with increasing wind penetration into the mulch. The dry density of the bermudagrass sod was 13.6 kg m^{-2}. It consisted of a soil layer with standing dormant grass stubble. The stubble was on average 0.04 m long, and the layer thickness of the soil it was standing in averaged 18 mm.

One may ask if the bermudagrass sod used in the laboratory accurately represented the mulch layer in the field; where does the mulch end and the soil begin? The dividing line between mulch and soil is not distinct, but very gradual and arbitrary. Therefore, mulch resistance was varied in the simulations to investigate its effect on soil temperature.

The heat flux between mulch and air is:

$$H_{ma} = \rho c_p \frac{T_{air} - T_{mulch}}{r_a} \qquad (6)$$

where T_{air} is air temperature (°C) and r_a is aerodynamic resistance (s m^{-1}). The latter was calculated as in ENWATBAL.BAS but using an aerodynamic roughness length based on a stubble length of the bermudagrass sod of 0.04 m (Van Donk and Tollner, 2000) using an equation by Campbell (1977):

$$z_0 = 0.026 \times h = 0.026 \times 0.04 = 0.00104 \qquad (7)$$

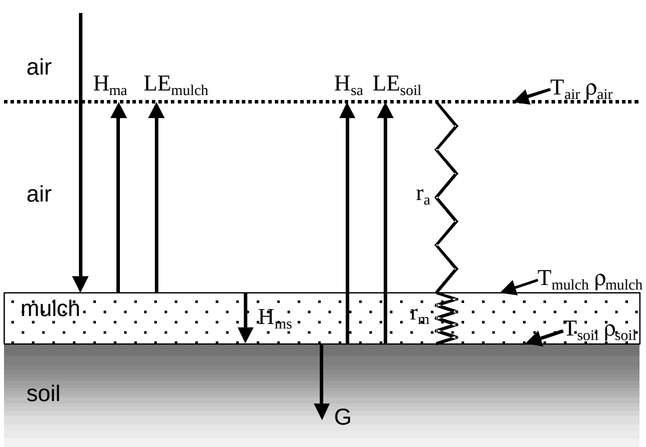

Figure 1. Fluxes and resistances in EWBM. Fluxes are shown in the direction that would occur in a typical daytime situation with a large amount of irradiance striking the mulch surface. The mulch energy balance (eq. 1) is made up of net radiation of the mulch (R_{nm}), sensible heat flux between mulch and air (H_{ma}), evaporation from the mulch (LE_{mulch}), and sensible heat flux between mulch and soil surface (H_{ms}). The soil surface energy balance (eq. 10) is made up of H_{ms}, soil heat flux at the soil surface (G), sensible heat flux between soil surface and air (H_{sa}), and evaporation from the soil surface (LE_{soil}). T_{air} is air temperature, T_{mulch} is mulch temperature, T_{soil} is soil surface temperature, ρ_{air} is absolute humidity of the air, ρ_{mulch} is absolute humidity of the mulch, ρ_{soil} is absolute humidity at the soil surface, r_a is aerodynamic resistance, and r_m is mulch resistance.

where z_0 is aerodynamic roughness length (m), and h is height of the roughness element (m).

The amount of water that the mulch holds varies between 0 and 5 mm. Water evaporation from the mulch is:

$$LE_{mulch} = L\frac{\rho_{air} - \rho_{mulch}}{r_a} \quad (8)$$

where L is latent heat of vaporization (J kg^{-1}), ρ_{air} is absolute humidity of the air (kg m^{-3}), and the absolute humidity of the mulch (ρ_{mulch}, kg m^{-3}) is:

$$\rho_{mulch} = \frac{1.323}{T_{mulch} + 273.16}\mathrm{EXP}\left(\frac{17.27 \times T_{mulch}}{T_{mulch} + 237.3}\right) \quad (9)$$

Equation 9 assumes that mulch water potential is always zero, independent from mulch water content. Some researchers used the same assumption (Hares and Novak, 1992), while others ignored water evaporation from the mulch (Ross et al., 1985; Chung and Horton, 1987; Bristow and Horton, 1996; Horton et al., 1996).

No exchange of longwave radiation was assumed between the soil surface and the dense mulch layer. This exchange would be valid if one were thinking about an exchange between two planes (e.g., plates) of different temperature. In our case, the space between the two "plates" is filled up with a dense mulch, effectively reducing longwave radiation exchange to zero. The situation can be compared with heat transfer between two different soil depths; in the case of soil, heat transfer is by conduction, perhaps also by convection, but not by thermal radiation.

Since no global irradiance reaches the soil surface, net radiation at the soil surface is zero. The soil surface energy balance (fig. 1) is then:

$$-H_{ms} + G + H_{sa} + LE_{soil} = 0 \quad (10)$$

where G is soil heat flux at the soil surface, H_{sa} is sensible heat flux between soil surface and air, and LE_{soil} is evaporation from the soil surface (all in W m^{-2}). Fluxes toward the soil surface are positive, except H_{ms}, which was previously defined as being positive when directed toward the mulch surface (eq. 1).

Soil heat flux at the soil surface is:

$$G = \lambda\frac{T_1 - T_{soil}}{\Delta z} \quad (11)$$

where λ is soil thermal conductivity (W m^{-1} °C^{-1}), T_1 is temperature at the center of the upper soil layer (°C), and Δz is distance between the soil surface and the center of the upper soil layer (m).

Sensible heat flux between soil and air (H_{sa}) is:

$$H_{sa} = \rho c_p \frac{T_{air} - T_{soil}}{r_m + r_a} \quad (12)$$

Evaporation of water from the soil surface is:

$$LE_{soil} = L\frac{\rho_{air} - \rho_{soil}}{r_m + r_a} \quad (13)$$

where ρ_{soil} is absolute humidity at the soil surface (kg m^{-3}). Soil surface humidity is a function of soil water potential of the upper soil layer:

$$\rho_{soil} = \rho_{pot}\mathrm{EXP}\left(\frac{ppot_1}{46.97(T_{soil} + 273.16)}\right) \quad (14)$$

where ρ_{pot} is potential absolute humidity at the soil surface (kg m^{-3}), and $ppot_1$ is soil water potential (m) of the upper soil layer.

$$\rho_{pot} = \frac{1.323}{T_{soil} + 273.16}\mathrm{EXP}\left(\frac{17.27T_{soil}}{T_{soil} + 237.3}\right) \quad (15)$$

The mulch (eq. 1) and soil surface (eq. 10) energy balances cannot be solved separately, as is done in ENWATBAL.BAS for the soil surface and crop energy balances. The reason for this is that in EWBM, T_{soil} and T_{mulch} appear in both energy balances. In ENWATBAL.BAS, T_{soil} only appears in the soil surface energy balance and T_{crop} only in the crop energy balance. In EWBM, the two energy balances are written as a system of two equations and two unknowns (T_{soil} and T_{mulch}). This system can be solved simultaneously, e.g., using the iterative Newton-Raphson algorithm (Sprott, 1991), which turned out to be very slow. Therefore, we chose to also solve a linearized version of the equations. Equations 3, 9, and 15 were linearized using the first-order Taylor series expansion about the known temperature (soil surface or mulch) of the previous time step (T_{pr}):

$$g(T) = f(T_{pr}) + (T - T_{pr})\frac{\partial f(T_{pr})}{\partial T_{pr}} \quad (16)$$

where g is the linearized equation, f is the nonlinear equation, and T is the unknown temperature (soil surface or mulch) of the current time step. Ham and Kluitenberg (1994) used the same procedure to linearize the Stefan-Boltzmann equation in their modeling study of the effect of plastic mulches on energy balance and soil temperature. Tracy et al. (1984) also used this procedure to linearize the Stefan-Boltzmann equation. In equation 14, the known soil temperature of the previous time step was used instead of the unknown current soil temperature.

After linearization, explicit expressions for T_{soil} and T_{mulch} were found using Maple software (Waterloo Maple, Inc., Waterloo, Ontario, Canada) and implemented in the BASIC code of EWBM (the explicit expressions are available upon request). Linearization introduces errors that should be kept small. The larger the difference between T and T_{pr}, the greater the linearization error is. Tracy et al. (1984) showed the magnitude of this error as a function of difference between T and T_{pr}. They also demonstrated the use of an iterative procedure to solve linearized equations, greatly reducing linearization errors when the difference between T and T_{pr} is large. To investigate the extent of linearization errors, simulation results from the linearized version of EWBM were compared with those from the nonlinear, Newton-Raphson version of EWBM.

Simulations with ENWATBAL.BAS were conducted with a bare soil configuration (no crop or mulch). The soil profile depth used in the simulations was 1.77 m for both EWBM and ENWATBAL.BAS (table 1). Sixteen soil layers were used in the simulations, covering six physical soil horizons. Initial soil conditions at the beginning of the simulation are also shown in table 1. A minimum time step of 1 s and a maximum of 30 s were specified.

Hourly measured and simulated soil temperatures were compared using root mean square error (RMSE), bias, and efficiency or Nash-Sutcliffe coefficient. The RMSE is calculated as:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(T_{i\,\text{sim}} - T_{i\,\text{meas}}\right)^2} \tag{17}$$

where n is the number of temperatures (n = 192; 8 days times 24 hourly temperatures), $T_{i\ \text{sim}}$ is the ith simulated temperature, and $T_{i\ \text{meas}}$ is the ith measured temperature. Bias is calculated as:

$$\text{Bias} = \frac{1}{n}\sum_{i=1}^{n}\left(T_{i\,\text{sim}} - T_{i\,\text{meas}}\right) \tag{18}$$

The efficiency or Nash-Sutcliffe coefficient is calculated as:

$$\text{Efficiency} = 1 - \frac{\sum_{i=1}^{n}\left(T_{i\,\text{sim}} - T_{i\,\text{meas}}\right)^2}{\sum_{i=1}^{n}\left(T_{i\,\text{sim}} - T_{\text{avg}\,\text{meas}}\right)^2} \tag{19}$$

where $T_{\text{avg meas}}$ is average measured temperature.

Field Data

Simulations were conducted for a dormant bermudagrass “mulch” on a Cecil sandy loam, at the USDA-ARS J. Phil Campbell, Senior, Natural Resource Conservation Center in Watkinsville, Georgia (33.86° N, 83.44° W, elevation = 253 m). Tifton 78 bermudagrass was planted at the experimental site in 1985 and harvested as hay. A pit approximately 1 m wide, 3 m long, and 1.8 m deep was excavated in 1994. Soil horizons were identified (L. West, personal communication, 1994) to determine placement of copper-constantan soil thermocouples, which were installed horizontally in the pit walls at ten depths: 0.04, 0.07, 0.12, 0.25, 0.47, 0.66, 0.88, 0.99, 1.20, and 1.50 m. Six sets (replications) of thermocouples were installed in the pit, three on each wall, for a total of 60 thermocouples. The pit was refilled with the same soil and packed to obtain, as closely as possible, the same bulk density as the original soil. A cover of bermudagrass was reestablished over the excavated area. Properties of this bermudagrass in dormant state were presented with equations 4 and 5.

Soil temperature was measured every 10 s using a CR21X datalogger and an AM416 multiplexer (Campbell Scientific, Logan, Utah). Averages were recorded every 15 min. Hourly weather data (totals and averages of measurements taken every minute) were available from an automated weather station (Hoogenboom, 1993), located 200 m from the site. Data included precipitation, air temperature, relative humidity, solar irradiance, and wind speed.

Water retention data were obtained in the laboratory according to a method described by Klute (1986) using undisturbed soil cores from each of the six horizons. Hydraulic conductivity was not measured at the exact site location. We used hydraulic conductivity data measured in situ on a plot located 200 m from the site (Southern Cooperative Series, 1983, plot 4, table B46). The saturated hydraulic conductivity was taken as the saturated hydraulic conductivity as determined on soil cores (Southern Cooperative Series, 1983), except for those horizons where this was lower than the greatest hydraulic conductivity from the in situ observations. In such a case, the latter was taken as the saturated conductivity instead of the core data.

Results and Discussion

Simulations were conducted for a period of eight days in December 1995 using hourly weather data. There was no precipitation during this period, and air temperatures were around the freezing mark (table 2). Simulations with ENWATBAL.BAS yielded daily soil temperature amplitudes of about 12°C at a depth of 0.04 m (fig. 2). With EWBM, the simulated amplitudes were approximately 3.5°C, much closer to measured amplitudes of about 2.5°C. The RSME was 4.1°C for simulations with ENWATBAL.BAS (table 3). It was reduced to 1.1°C when simulating with EWBM.

At a depth of 0.25 m, the RMSE was 0.3°C when simulating with EWBM, compared to an RMSE of 1.1°C resulting from simulation with ENWATBAL.BAS. At a depth of 0.47 m, measured daily temperature amplitudes were reduced to about 0.1°C, whereas simulated amplitudes were 0.2°C with EWBM and 0.5°C with ENWATBAL.BAS. At 0.66 m depth, both measured amplitudes and those simulated with EWBM were 0.0°C, whereas ENWATBAL.BAS simulated amplitudes of 0.2°C. At 0.88 m depth, amplitudes were 0.0°C, whether measured or simulated using either version of the model.

Because of uncertainties in the exact value of the mulch resistance (as discussed before), it was varied. Multiplying the mulch resistance by 1.5 resulted in better agreement between simulated and measured data at a depth of 0.04 m, but agreement was worse at 0.25 m (fig. 2). At this latter depth, the RMSE and the bias increased, and the efficiency decreased (table 3). The increased mulch resistance reduced simulated daily soil temperature amplitudes, as expected. EWBM was sensitive to variations in mulch resistance, with simulations becoming worse as mulch resistance decreased. EWBM was much less sensitive to variations in mulch albedo (table 3).

Measured temperatures lagged behind simulated temperatures (fig. 2). In soil, a lag time is attributed to the fact that heat flux is mostly by conduction, and the lag time for deeper depths arises naturally from the heat equation (Fourier’s Law for conductive heat transfer coupled with the energy conservation equation). This leads to the hypothesis that we are missing the physical process of conduction of heat through the mulch, which would introduce a lag time, unlike the instantaneous sensible heat flux model that we used exclusively for heat flux through the mulch (fig. 1). Another reason for the differences between measured and simulated soil temperatures could be incorrect estimation of soil thermal conductivity.

Soil water content at a depth of 0.04 m simulated with EWBM was greater than that simulated with ENWATBAL.BAS, as expected (fig. 3). On the first day of the simulation (day 356), the difference was not yet very large. There was not much drying power on this cloudy, cool, and humid day (table 2). On the next day (357), there was much more drying power, and on this day there was a large

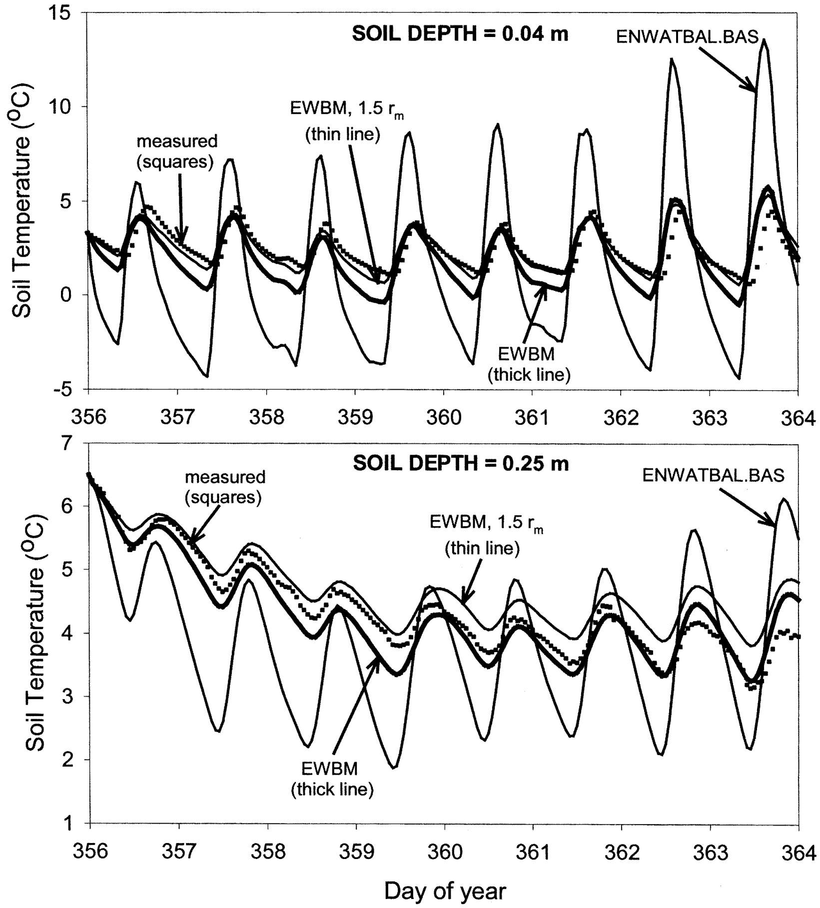

Figure 2. Simulated and measured soil temperature at two soil depths for eight days in December 1995, Watkinsville, Georgia. For each soil depth, three simulations are shown: ENWATBAL.BAS, EWBM, and EWBM with the mulch resistance (r_m) multiplied by 1.5.

Table 3. Comparison of hourly measured and simulated soil temperatures at two soil depths in terms of root mean square error (RMSE), bias, and efficiency. Mulch resistance and mulch albedo were varied in simulations with EWBM.[a]

	Soil Depth = 0.04 m						Soil Depth = 0.25 m					
	RMSE (°C)		Bias (°C)		Efficiency		RMSE (°C)		Bias (°C)		Efficiency	
Simulation	Avg	SE	Avg	SE	Avg	SE	Avg	SE	Avg	SE	Avg	SE
ENWATBAL.BAS	4.10	0.11	-0.99	0.13	0.19	0.04	1.13	0.05	-0.56	0.08	0.19	0.02
EWBM	1.10	0.09	-0.50	0.13	0.51	0.06	0.30	0.04	-0.11	0.08	0.83	0.04
EWBM, $r_m \times 2$	0.89	0.09	0.59	0.13	0.37	0.05	0.71	0.08	0.66	0.08	0.27	0.05
EWBM, $r_m \times 1.5$	0.76	0.07	0.09	0.13	0.57	0.06	0.39	0.06	0.30	0.08	0.68	0.07
EWBM, $r_m \times 0.67$	1.60	0.10	-0.88	0.13	0.40	0.05	0.54	0.07	-0.40	0.08	0.64	0.05
EWBM, $r_m \times 0.50$	1.93	0.10	-1.04	0.13	0.35	0.05	0.69	0.07	-0.53	0.08	0.52	0.05
EWBM, albedo = 0.15	1.13	0.09	-0.27	0.13	0.52	0.07	0.33	0.03	0.03	0.08	0.77	0.03
EWBM, albedo = 0.35	1.13	0.09	-0.73	0.13	0.47	0.05	0.34	0.07	-0.26	0.08	0.81	0.06

[a] Avg = average, SE = standard error (n = 6; six replications of soil temperature measurements).

difference between the two models. The mulch resistance in EWBM tempers evaporation, causing the soil to stay wetter than in ENWATBAL.BAS.

Simulation time decreased drastically when linearizing the EWBM equations. The linearized explicit solution method took 0.5 min for running an 8-day period on a 500 MHz Pentium III PC, compared with 27 min with the nonlinear Newton-Raphson method. Linearized EWBM was also faster than the less complex system (bare soil without mulch) simulated with ENWATBAL.BAS (1.3 min), which uses an iterative solution method to solve for T_{soil}. Results of simulations using nonlinear (Newton-Raphson) EWBM were compared with those produced by linear EWBM. Differences in simulated hourly soil temperature at a depth of 0.04 m were negligible, with the maximum difference being 0.01°C for a simulated period of eight days. This indicates that the linearizations created minimal error.

CONCLUSIONS

The ENWATBAL.BAS model was modified to enable mechanistic simulation of the effects of a dense mulch on the energy and water balance of a soil-mulch-atmosphere system. Two coupled energy balances, one for the mulch and one for the soil surface, replace the original soil surface

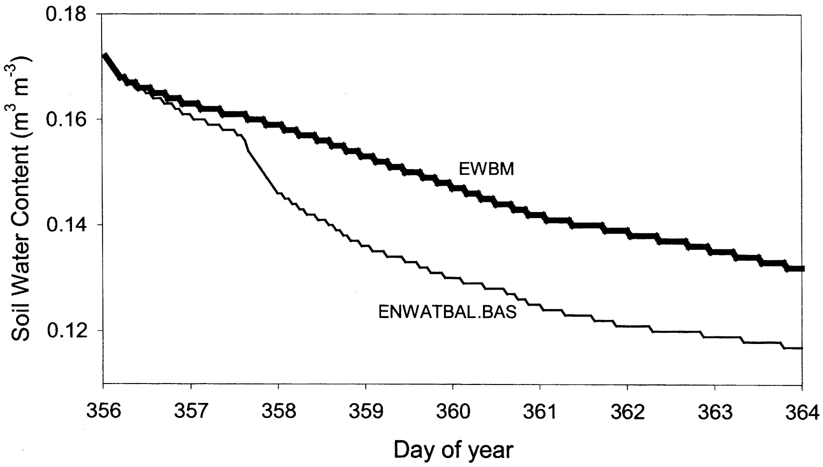

Figure 3. Simulated soil water content at 0.04 m for eight days in December 1995, Watkinsville, Georgia.

energy balance of ENWATBAL.BAS. An empirical mulch resistance to sensible and latent heat fluxes was introduced. Two solution methods were developed to simultaneously solve for the mulch and soil surface energy balances. The linearized, explicit method was 50 times faster than the nonlinear Newton-Raphson method, and linearization errors were negligible.

As a preliminary evaluation of the model, soil temperatures simulated with the modified model were compared with those measured at Watkinsville, Georgia, in Cecil sandy loam under a dense, thatchy layer of dormant bermudagrass that acted as a mulch during the simulation period. Simulated daily soil temperature amplitudes at a depth of 0.04 m were reduced from 12°C with ENWATBAL.BAS (configured for a bare soil) to 3.5°C when a mulch was introduced in the model. This corresponded much better with measured soil temperature amplitudes of about 2.5°C. The RMSE was reduced from 4.1°C using ENWATBAL.BAS to 1.1°C using EWBM. Further data are needed to fully validate the approach.

An important component of heat movement through the mulch may to be due to conduction. This process is not modeled by EWBM. Additional study is required to elucidate the relative importance of sensible heat flux vs. conductive heat flux through the mulch. Further research and model development should focus on generalizing the mulch component of the model. Such a model should accommodate less dense mulches where solar irradiance is not necessarily all dissipated at the top of the mulch, as is the case in EWBM. It would be partitioned over canopy, mulch, and soil surface. Partitioning would be a function of leaf area index and residue area index.

In addition, a more general model should have a less empirical approach to determine the mulch resistance. Rather than measuring it for each mulch, the mulch resistance should be determined from basic mulch properties such as mulch thickness and bulk density in combination with environmental variables such as wind speed, which may penetrate the mulch and thus alter its resistance. The inclusion of a crop canopy would also make the model more complete, modeling a soil-mulch-crop-atmosphere system rather than only a soil-mulch-atmosphere system as it does now. The capability to simulate a wide variety of mulches would greatly increase the scope of problems to which ENWATBAL may be applicable.

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