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MODELING THE EFFECT OF SOIL, VEGETATION TYPE AND DENSITY ON SOIL MOISTURE AND SURFACE ENERGY FLUX

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Soil moisture plays a crucial role in hydrological modeling and land-atmosphere energy balance by controlling the amount of evaporation and thermal heat exchange between the land surface and overlying atmosphere. This energy exchange in turn plays a vital role in modifying atmospheric dynamics, including small-scale phenomena such as thunderstorms as well as larger-scale events such as droughts and floods. Understanding the relationships between the soil moisture distribution in the profile with properties such as surface temperature, radiation balance, evaporation, and infiltration is important in order to forecast hydrological and meteorological processes. The SHEELS (Simulator for Hydrology and Energy Exchange at the Land Surface) numerical model is designed to estimate the movement of water within the soil as well as surface temperature and energy exchange for various agricultural management practices. In 1998, the study was conducted on six plots composed of two 50 x 60 m and four 30 x 50 m plots, one bare, one grass and four corn plots having four different vegetation densities Corn 4, Corn 3, Corn 2, and Corn 1. The SHEELS model was applied using data collected from Huntsville '98, a field experiment performed to measure soil properties with sensors buried in the soil. A model simulation was performed for four plots, bare soil, Corn 4, Corn 2, and grass over 12 days. Bare soil exhibited higher surface temperature throughout the study period. Due to the increased interception by the corn full canopy, Corn4 plot had lower near surface soil moisture. Model simulations are quite consistent with measurements, however model soil moisture responds too strongly to rainfall. Soil water dynamics are strongly controlled by soil hydraulic properties that have extremely high spatial variability.

INTRODUCTION

Soil moisture plays a crucial role in the land-atmospheric energy balance by controlling the amount of evaporation and thermal heat exchange between the land surface and overlying atmosphere. This energy exchange in turn plays a vital role in modifying atmospheric dynamics, including small-scale phenomena such as thunderstorms, as well as large-scale events such as floods and droughts. An understanding of the relationships between the vertical profile of soil moisture with properties such as surface temperature, radiation balance and evaporation with and without vegetation is important in regional and global scale hydrological and meteorological forecasting.

Many studies have shown that variations in surface conditions have considerable influence on mesoscale processes through radiative or heat-moisture flux exchange. For example, Pinty et al., (1989) used an evapotranspiration model coupled with a two-dimensional mesoscale model and found that significant mesoscale circulations developed around a vegetation type discontinuity when soils are moist, whereas the circulation weakened when the soils were dry. An earlier modeling study by Ookouchi et al., (1984) had noted that mesoscale circulation would develop as the result of soil moisture discontinuities. Another study by Mahfouf et al., (1987) also found changes in horizontal and vertical wind fields above discontinuities in soil type and vegetative cover. In a case study Rabin et al., (1990) found that convective cloudiness, in the absence of large-scale disturbances, was associated with surface temperature differences resulting from nonuniform vegetative cover. Since the surface-atmosphere interactions are two-way, it is necessary to develop physical models of surface and subsurface processes which are computationally simple, yet allow the surface to interact with the atmosphere.

The land surface flux-hydrology model used in this study is SHEELS (Simulator for Hydrology and Energy Exchange at the Land Surface), a model based on the Biosphere-Atmosphere Transfer Scheme (BATS) of Dickinson et al., 1993. SHEELS has retained the treatment of vegetation properties and the surface flux parameterizations of BATS. All relevant hydrologic and energy processes are modeled to determine moisture in each soil layer. Formulations of variables such as surface energy fluxes and temperatures in SHEELS are similar to those in an earlier version of the model (Smith et al., 1993). However, subsurface hydrologic processes have been significantly modified. The major modification in the model relates to the configuration of the soil layers. Previously, the model had three layers (called upper, root and total) which were nested - the root layer contained the upper layer and the total layer contained the root layer. This was changed to a discrete layer configuration so that the layers are not nested, resulting simpler and more intuitive water budget equations. In the following discussion, subscripts *u*, *m*, and *b* refer to the three layers, now called upper, middle and bottom. The tendency equations for water depths (d_{wu}, d_{wm}, and d_{wb}) in each of the layers are as follows:

Upper Layer:

$$\partial d_{wu} / \partial t = (1-\sigma_f)\, P_r + P_d + \lambda_u - D_u - R_u - E_g - r_{tr} E_{tr} \tag{1}$$

Middle Layer:

$$\partial d_{wm} / \partial t = l_m - l_u + D_u - D_m - (1-r_{tr}) E_{tr} \tag{2}$$

Bottom Layer:

$$\partial d_{wb} / \partial t = \lambda_m + D_m - D_b \tag{3}$$

where σ_f is the fractional vegetation cover, P_r the precipitation rate and P_d the rate of precipitation reaching the soil surface from canopy drip. Upper and middle layer diffusion rates are denoted as λ_u, λ_m, D_u, D_m, and D_b are gravitational drainage rates at the bottom of each layer. The quantity r_{tr} is the fractional contribution to transpiration by the upper layer, E_g represents the rate of evaporation from the soil, and E_{tr} is the transpiration rate. The units all terms are in mm/sec.

The nested three-layer approach of BATS has been converted to a discrete layer configuration in SHEELS, in which the number and depth of layers is flexible. This permits higher vertical resolution near the surface where temperature and moisture gradients are large.

SHEELS is driven by seven atmospheric forcing variables - air temperature, relative humidity, atmospheric pressure, incident solar and infrared radiative fluxes, wind speed and precipitation. SHEELS also requires spatially distributed soil properties, including saturated hydraulic conductivity, saturated matric potential, rooting depth and porosity. Required vegetation properties include canopy height, fractional vegetation cover, minimum stomatal resistance, leaf area index, and albedo.

The output of SHEELS consists primarily of surface energy fluxes and associated temperature and moisture state variables. SHEELS estimates volumetric water content at each time step for each soil layer. The temporal change in soil moisture content in each of the soil layers is determined via a water balance approach by considering the contributions of infiltration, evaporation, transpiration, diffusion, and gravitational drainage. Surface runoff and ponded water are also calculated. Infiltration is calculated using the Green-Ampt equation based on the amount of precipitation reaching the soil surface directly or through the vegetation canopy. Surface runoff is based on local slope angle and infiltration excess. The amount of water reaching the soil surface which does not run off or infiltrate is assumed to pond on the surface. The amount of water extracted via transpiration is distributed to the bottom of the root zone, while infiltration and evaporation affect a shallower layer. After water depths have been updated to account for infiltration, evaporation, and transpiration, volumetric water contents are updated and the effect of three-dimensional diffusion and drainage processes on soil moisture is determined. The vertical fluxes of water between each layer and lateral subsurface flow are calculated using Darcy's law (Darcy, H. 1856).

OBJECTIVE

The objective of this research is to estimate the movement of water within the soil as well as surface temperature and energy exchange for various agricultural management practices.

MATERIALS AND METHODS

The research was conducted at Alabama A&M University, Winfred Thomas Agricultural Experiment Station located near Hazel Green Alabama. In 1998, the study was conducted on six plots composed of two 50 x 60 m and four 30 x 50 m plots, one bare, one grass and four corn plots having four different vegetation densities Corn 4, Corn 3, Corn 2, and Corn 1. Automated systems were used to continuously measure meteorological conditions, soil moisture and temperature in the soil profile to a depth of 90 cm. Volumetric water content was measured at five depths (5, 15, 30, 60, and 90 cm) in all four plots with CS615-L Water Content Reflectometry (WCR) manufactured by Campbell Scientific, Inc. Within each plot a Double-Sided Pyranometer and a Total Hemispherical Radiometer from Radiation and Energy balance Systems, Inc. were installed to measure incoming and reflected solar radiation and incoming and outgoing all-wave radiation. In each plot and at all five soil depths, soil temperature probes were also installed. Heat flux plates were deployed at 5 cm depth and a tipping bucket raingage was installed on each plot. Air temperature, relative humidity and wind speed and direction were also measured at the field site. In this project, SHEELS was applied using data collected from this experiment and model simulations were performed for bare, grass, and CF and C1/3 plots, for a two week experimental period.

RESULTS AND DISCUSSION

The soil at this site is a Decatur silt loam, although the grass plot is silty clay loam, having clay content near the surface in excess of 30% (Tsegaye, et al., 1997). Clay contents increase with depth in all plots. In the upper 15 cm, the soil porosity was in the range 0.4 to 0.5. Saturated hydraulic conductivity decreased from 0.03 mm s^{-1} in the upper 8 cm layer to 0.003 mm s^{-1} at 60 cm depth. The bulk density values for the site range from 1.35 g cm^{-3} near the surface to 1.55 g cm^{-3} at 60 cm depth. Four precipitation events occurred during the field experiment (Figure 1). A total amount of 4.84 cm of water was recorded during this period. The two major rainfall events occurred on days 170 and 176.

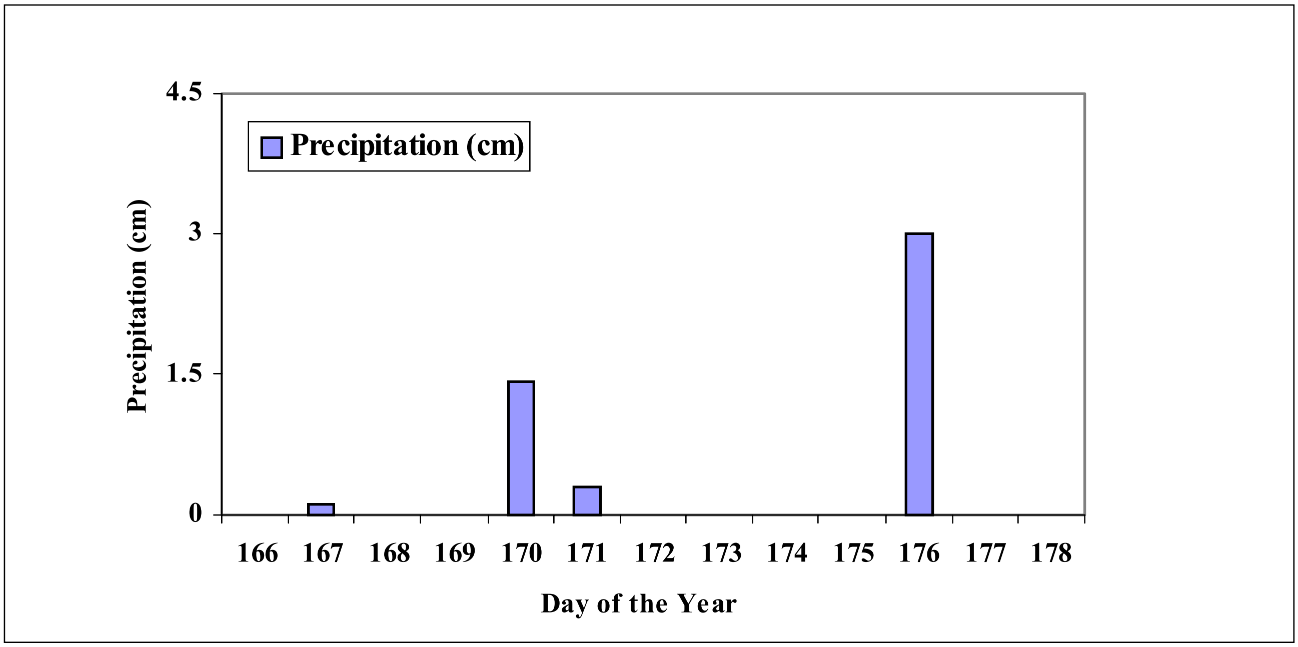

Figure 1. Daily precipitation during the Huntsville Field experiment.

SHEELS was applied to simulate conditions on each of the four plots (bare, Corn-4, Corn-2 and grass), for days 166-178. In these simulations, measurements of vegetation properties (canopy height, fractional vegetation cover, and leaf area index) for each site were used to represent the inter-site canopy variations (Figure 2). Field-scale means of soil properties (saturated hydraulic conductivity, porosity, bulk density) are used across the four plots. Initial moisture conditions in each of the three SHEELS soil zones are set based on field measurements. The soil layers within the root zone (surface to 40 cm) are 2 cm thick, and lower layers are 10 cm deep. The total depth of the soil column is 2 m. The time step is 15 minutes.

Figure 3 shows a comparison of SHEELS-estimated surface temperatures at three of the plots; Corn-2 is not shown but is very similar to Corn-4. For the vegetated plots, surface temperature represents a composite of the bare and vegetated surfaces. The fractional vegetation cover for the grass and Corn-4 plots was 0.9. In Figure 3, it is seen that the daytime maximum surface temperatures for the bare plot are much more variable than for the vegetated plots. When the soil is dry, such as

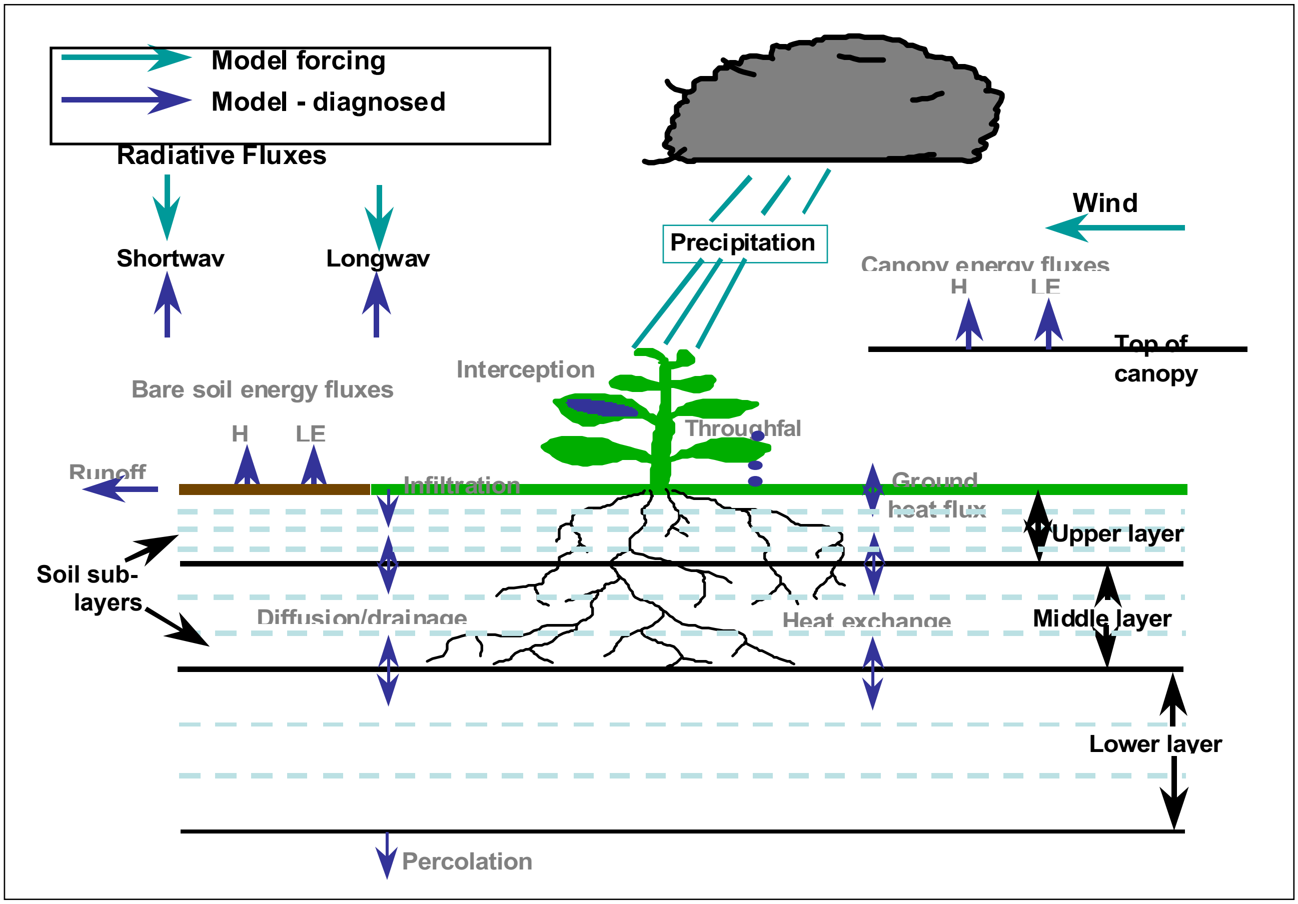

Figure 2. Simulator for Hydrology and Energy Exchange at the Land Surface (SHEELS) - Physical Processes.

days 168-169 and 174-176, the bare surface temperature is higher than for the other plots, whereas under wet conditions such as days 170-172 and 177, the bare surface is cooler. The grass plot is usually warmer during the day than Corn-4. At night, differences between the plots are very small, as the surface temperature is nearly in equilibrium with air temperature.

A comparison of modeled and measured surface temperatures is shown in Figure 4 for the Corn-4 plot. Measured temperatures were obtained from a radiation balance approach. Deployed at each plot except Corn-2 were a Double-Sided Pyranometer and a Total Hemispherical Radiometer built by Radiation and Energy Balance Systems (REBS, Inc.). The former device measures incoming and reflected solar radiation, while the latter measure incoming and outgoing all-wave radiation. Together these provide all four components of the surface radiation balance; surface temperature was derived from the upwelling longwave radiation, assuming an emissivity of 0.975. Daytime maximum SHEELS-estimated surface temperatures for the Corn-4 plot are consistently about 10K lower than measured and about 2K lower at night. These differences could be ascribed to the model physics or parameters such as fractional vegetation cover and vegetation albedo. However, there are other likely source of errors, including measurement error, non-representativeness of the radiometer measurements, and the assumed value of emissivity. Measured bare surface temperatures (not shown) are generally higher than for Corn-4, and temperatures for the grass plot is lower than Corn-4. These relationships are consistent with the model results shown in Figure 3.

Fractional water content (proportion of soil porosity) estimated by SHEELS at 3 cm depth is

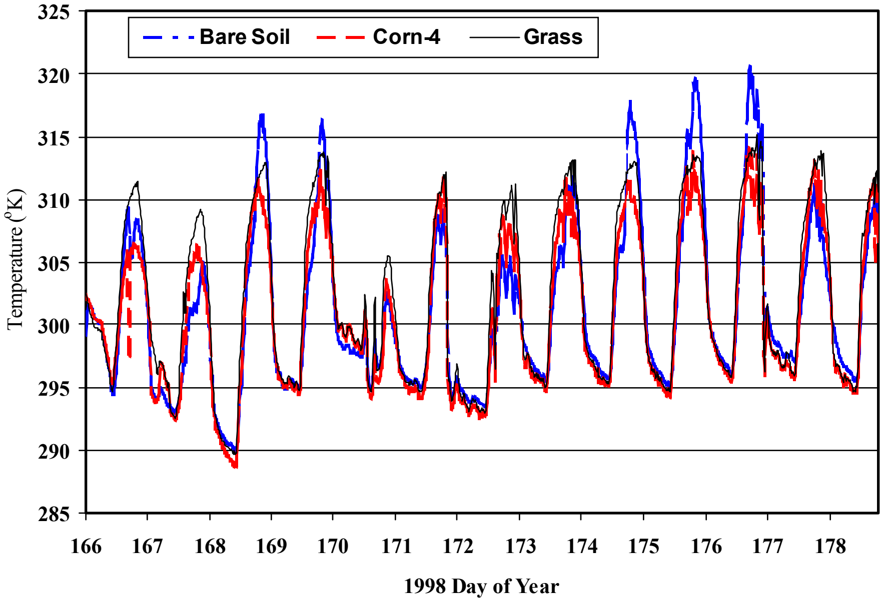

Figure 3. Estimation of surface temperature by SHEELS for bare soil, Corn-4, and grass plot.

shown for all plots in Figure 5. These time series show that the Corn-4 plot has the lowest near-surface soil moisture. This appears to be due to the increased interception by the full corn canopy. At the

For theCorn-4 plot, SHEELS estimates that only 41.0 of the 47.1 mm of water reaching the canopy from precipitation and irrigation infiltrated the soil. For the Corn-2 plot, infiltration was 35.0 mm of the 37.4 mm applied, and for the grass plot, the ratio was similar at 35.5/37.4. The initial soil moisture at the Corn-4 plot was also lower, possibly because of prior rainfall interception or greater evapotranspiration relative to the other plots. The time series of 3-cm soil moisture at the other three plots is similar, except during periods of irrigation on days 166-167. The bare plot exhibits higher diurnal amplitude, as a shallow surface layer dries during the day and is recharged from below at night. This is seen to a lesser extent in the Corn-2 results.

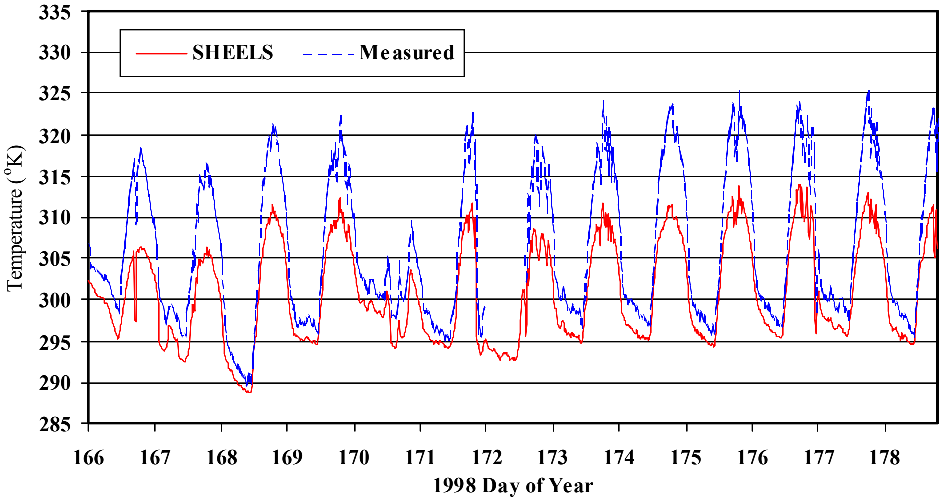

Figure 4. SHEELS vs. measured surface temperatures for Corn-4 plot.

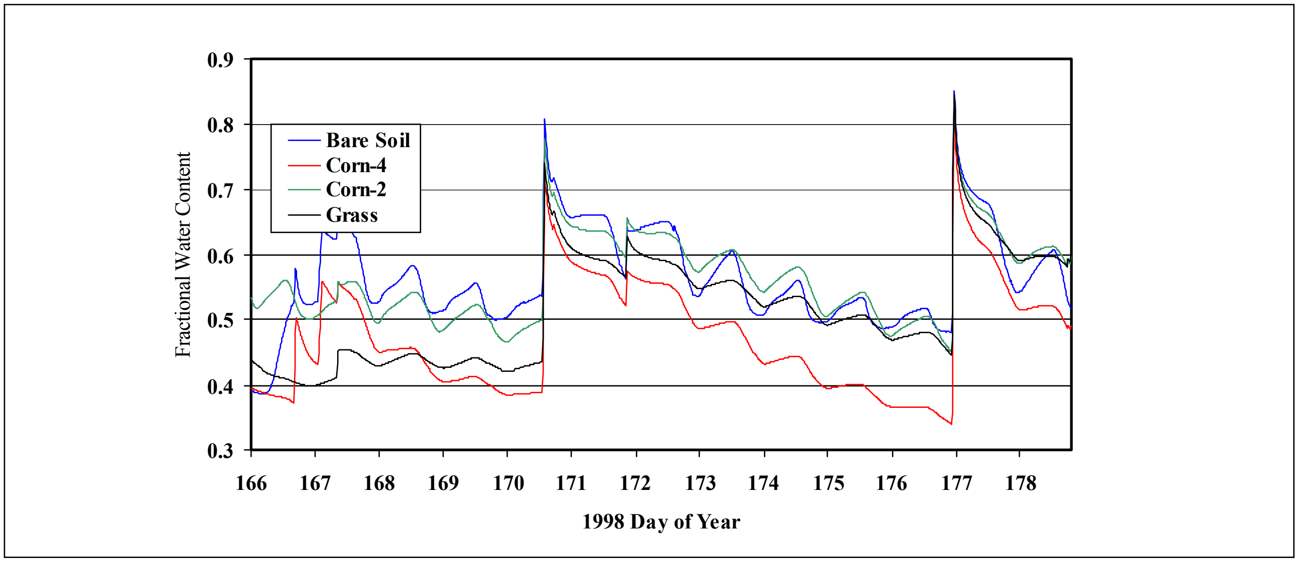

Figure 5. Soil moisture estimated by SHEELS for 3-cm soil depth.

The SHEELS-estimated root zone soil moisture shown in Figure 6 illustrates the role of the vegetation in controlling soil moisture. The order of the plots, from driest to wettest, is determined by the amount of vegetation. Throughout the experiment, the soil at 20 cm depth is driest in the Corn-4 plot, for reasons discussed above. The wettest conditions at this depth are found at the bare plot. Because of the absence of roots, water is not extracted from the soil through transpiration.

Soil moisture was measured at several depths at each plot using a model CS615 Water Content Reflectometer, manufactured by Campbell Scientific, Inc. The CS615 is based on time domain reflectometry, in which an electrical pulse is transmitted down a pair of steel probes, reflected from the probe ends and subsequently received at the base. The elapsed time is a function of the moisture in the soil surrounding the probes. The time period was related to water content in a post-experiment laboratory calibration procedure using soil cores from each plot. Measurement uncertainty was determined to be less than 0.08 of the fractional water content.

Comparisons of 3 cm and 10 cm soil moisture for the bare and Corn-4 plots are shown in Figures 7 and 8. For the bare plot, simulations are quite consistent with measurements. The main disparity observed in this comparison is that the model soil moisture responds too strongly to rainfall, and thus

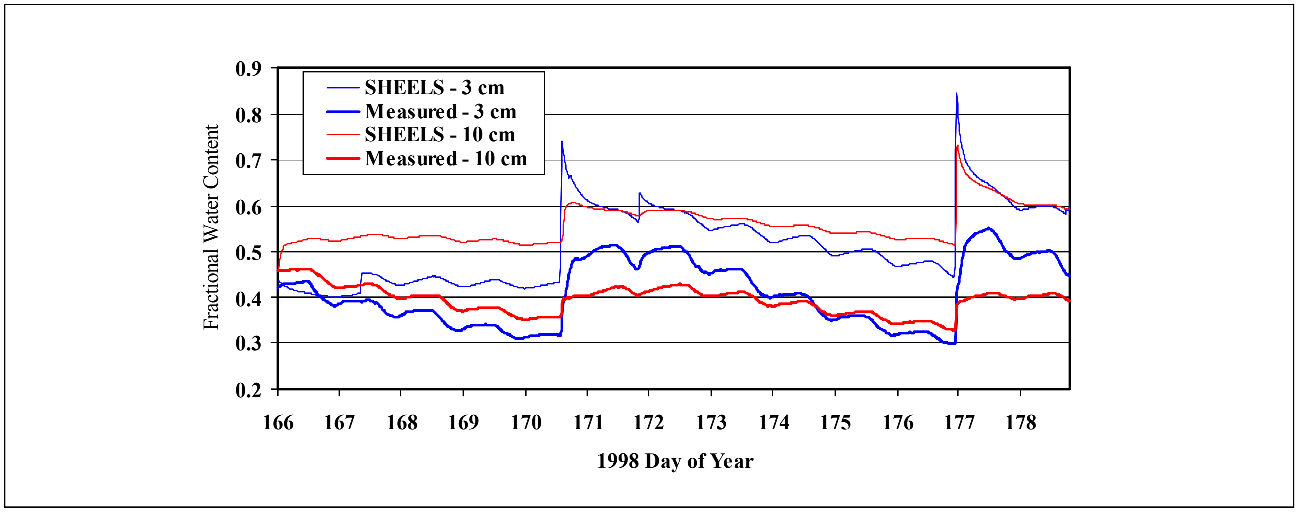

Figure 6. SHEELS vs. measured soil moisture content at 3 cm and 10 cm for the grass plot.

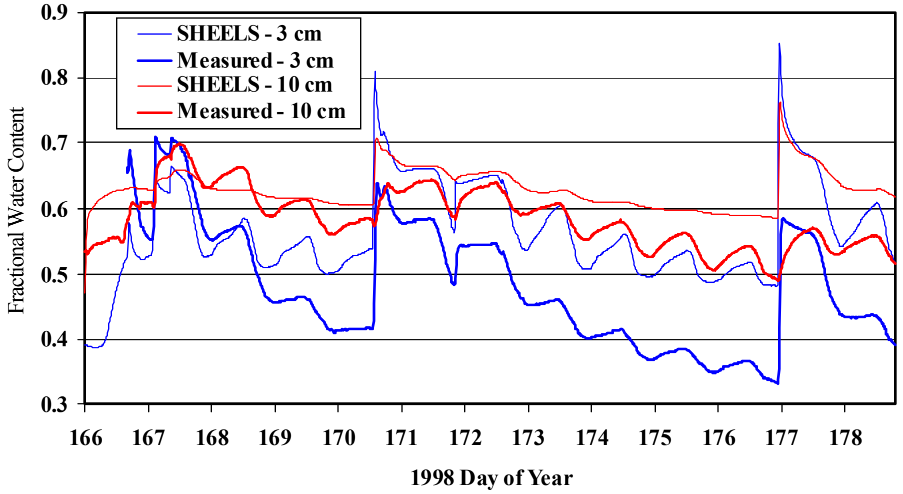

Figure 7. SHEELS vs. measured soil moisture at 3 cm and 10 cm for the bare plot.

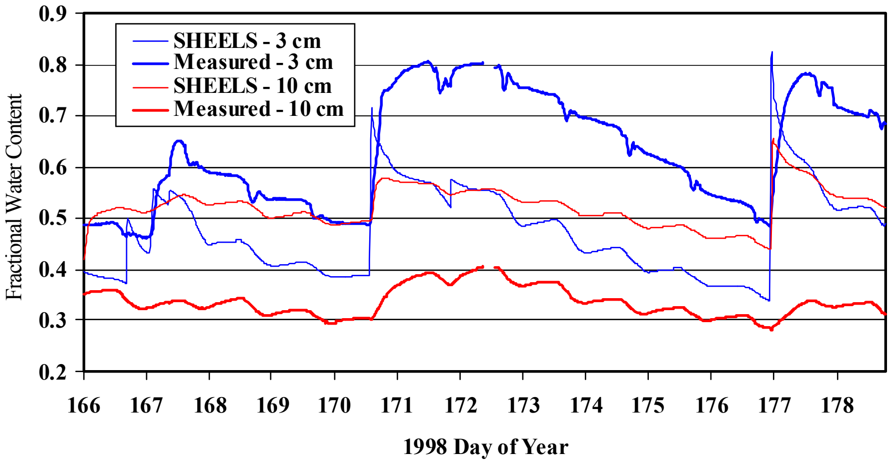

Figure 8. SHEELS vs. measured soil moisture at 3 cm and 10 cm for Corn-4 plot.

stays slightly wetter than the measurements. At the Corn-4 plot, simulation results are quite different from the measured values. Model soil moisture is higher than the measurements at 3 cm, and lower at 10 cm. This indicates that the soil parameter values, most importantly saturated hydraulic conductivity, may not be representative of conditions at Corn-4. Using a lower hydraulic conductivity at this plot would have resulted in slower movement of water through the soil column and would have given results more consistent with the observations. This points out a serious difficulty in modeling soil hydrologic processes. Soil water dynamics are strongly controlled by soil hydraulic and physical properties that have extremely high spatial variability. Even at the field scale, variations in measured saturated hydraulic conductivity can be at least one order of magnitude, and thus representativeness is always an issue.

CONCLUSION

The SHEELS model was used to simulate both surface soil moisture and surface temperature for four plots, bare soil, Corn 4, Corn 2, and grass. Bare soil exhibited higher surface temperature throughout the study period. Due to higher interception of rainfall by the corn full canopy, Corn4 plot had exhibited lower near surface soil moisture as compared to all other plots. Model simulations are quite consistent with measurements, however model soil moisture responds too strongly to rainfall. Soil water dynamics in the upper few centimeters of the soil profile are strongly controlled by soil hydraulic properties that have extremely high spatial variability.

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