The Influence of Soil Moisture on the Surface Energy Balance in Semiarid Environments

By

Eric E. Small
Principal Investigator
Department of Earth and Environmental Science
New Mexico Tech

and

Shirley Kurc
Research Assistant
Department of Earth and Environmental Science
New Mexico Tech

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Abstract

The objective of this research was to test the following hypothesis regarding the nature of the soil moisture-rainfall feedback in semiarid regions**.** There is a dramatic land surface response to precipitation events and the associated rise in soil moisture, but this response is limited in duration. In addition, plant type does not influence the nature of this response. We tested this hypothesis by measuring the surface water and energy balances at three locations across the shrub-ecotone in the Sevilleta Wildlife Refuge. Measurements spanned the entire 2000 monsoon season.

Our analysis yielded four major results. First, changes in the evaporative fraction (EF) resulting from wet versus dry soil moisture conditions are dramatic. When the soil is dry, the evaporative fraction is typically 0.1, demonstrating that only 10% of the energy transferred from the surface to the atmosphere is via latent heating. In contrast, the evaporative fraction is ~0.5 when the soil is wet. This demonstrates that the surface energy balance (SEB) response to rainfall, at least in terms of latent heating, is substantial and could yield a feedback to the atmosphere. Second, net radiation and available energy both increase when the soil is wet, in both the grass and shrub environments. A volumetric water content change of ~5% yields an increase of 50 W m^{-2}. If this result is accurate, then the soil moisture-net radiation feedback proposed by Eltahir (1998) would contribute to soil moisture-rainfall feedbacks in semiarid regions such as the Sevilleta. Third, changes in EF and net radiation following rainfall events are short lived – persistence is on the order of days. Therefore, a soil-moisture rainfall feedback will only exist if the atmospheric conditions conducive for convective precipitation occur within several days after a rainfall event. Fourth, the evaporative fraction and net radiation response to rainfall and the persistence of anomalous conditions are nearly identical across the grass-shrub ecotone. Therefore, we conclude that plant type does not influence the nature of soil moisture-rainfall feedbacks in semiarid regions.

Table of Contents

1. Objectives

The state of the Earth's land surface affects the atmosphere above it, via the surface-atmosphere fluxes of water, energy, and momentum (Shukla and Mintz 1982; Shuttleworth 1991). Soil moisture strongly controls the nature of these fluxes, including the partitioning of available energy between latent and sensible heating (Entekhabi and Rodriquez-Iturbe 1994) and the magnitude of net radiation absorbed by the surface (Eltahir 1998). The soil moisture reservoir evolves on timescales as long as seasons or even years (Vinnikov et al. 1996). Therefore, soil moisture acts as a source of long-term "memory" of past precipitation events (Entekhabi et al. 1996). Because soil moisture both reflects past precipitation and influences the state of the overlying atmosphere, it has been hypothesized that a positive feedback may exist between soil moisture and rainfall; above (below) normal rainfall yields high (low) soil moisture, which in turn yields additional (limited) rainfall. If a positive soil moisture-rainfall feedback exists, then land surface memory due to soil moisture storage should amplify hydroclimatic variability, enhancing and prolonging both floods and droughts (Entekhabi et al. 1992).

The presence of a positive soil moisture-rainfall feedback, and the associated enhancement of variability, is supported by model experiments in which the effects of soil moisture anomalies on precipitation can be isolated (Rowntree and Bolton 1983). These experiments cannot be replicated in the "real world" because it is not possible to control all factors that influence precipitation. However, it is possible to correlate soil moisture anomalies with future precipitation (Findell and Eltahir 1997). It is also possible to identify relationships between soil moisture anomalies and surface fluxes or the state of the atmospheric boundary layer (BL). Data gathered from a tall grass prairie site in Kansas during the First ISLSCP Field Experiment (FIFE) (Sellers et. al. 1992) are consistent with, but do not prove that, a positive soil moisture-rainfall feedback exists. Betts and Ball (1998) and Eltahir (1998) found that when the soil was wet (dry), the surface-atmosphere fluxes and BL characteristics favored (inhibited) convective precipitation. Their results are intriguing, as they provide the first convincing field evidence of a physically ; based mechanism by which soil moisture can affect future rainfall.

Does a positive soil moisture-rainfall feedback exist in the southwestern U.S. or other semiarid regions? If it does, then the land surface, via soil moisture persistence, may contribute to temporal variability of summertime precipitation in these environments. Identifying if the land surface is a sources of precipitation variability in regions like the southwestern U.S. is critical to improve seasonal climate predictions (e.g., Gutzler and Preston 1997). It is not possible to directly assess if a soil moisture-rainfall feedback exists using only observed data. However, it is possible to determine if the relationship between soil moisture anomalies and BL conditions observed at FIFE, and therefore the potential for a feedback, exists in semiarid environments. Data from the FIFE site cannot be directly applied to semiarid regions, such as the southwestern U.S., because the hydroclimatological conditions are very different. Several field experiments focused on using remotely sensed data to estimate area averaged fluxes have been completed in semiarid environments (e.g., Monsoon '90, Waschita '92; Stannard et al. 1994; Kustas and Goodrich 1994). However, these experiments were relatively short (1-2 weeks), and therefore did not yield all the data needed to examine the soil moisture-rainfall feedback, which is a time-space phenomenon (Entekhabi and Rodriquez-Iturbe 1994). Previous modeling studies only provide rough information about the feedback, as model resolution was usually coarse and the imposed soil moisture anomalies were typically extreme (e.g., Oglesby 1991).

Here we explore the nature of the soil moisture-rainfall feedback in semiarid regions using field observations from the Sevilleta National Wildlife Refuge (Figure 1). We test the following hypothesis concerning the strength of land-atmosphere interactions in the southwestern U.S. during the summer monsoon season. Compared to wetter regions (e.g., Kansas), the influence of soil moisture conditions on BL characteristics, and therefore on future convective rainfall, is relatively weak. The link is weak because the anomalies of soil moisture and attendant surface fluxes are spatially heterogeneous at the lengthscale over which the BL averages (~10-100 km) (Andre et al. 1990; Betts and Ball 1998). We propose that the land surface is "disorganized" (Shuttleworth 1988) as a result of interactions between minimal hydrologic persistence and the spatial variability of convective precipitation (Houze 1981). In addition, we propose that the influence of heterogeneous vegetation on spatial variability of soil moisture and surface fluxes is minor compared to the effects of transient soil moisture anomalies. If our hypothesis is correct, then land surface processes should have a negligible impact on hydroclimatic variability in the southwest, and the observed variability must arise from only oceanic and atmospheric processes.

1.1 Soil moisture-rainfall feedback

Model experiments: Various types of models show that a positive soil moisture-rainfall feedback should exist (Rowntree and Bolton 1983; Entekhabi and Rodriguez-Iturbe 1994; Castelli and Rodriguez-Iturbe 1996; Zheng and Eltahir 1998). Statistical models provide information regarding the temporal and spatial distribution of soil moisture anomalies, given a set of general conditions about land surface hydrology. However, they typically do not capture the complex interactions between various land surface and atmospheric processes or the effects of variable vegetation (e.g., Entekhabi and Rodriguez-Iturbe 1994). In studies using sophisticated coupled land-atmosphere models, the imposed soil moisture anomalies are typically drastic and applied over extensive regions, and therefore may not provide useful estimates of the strength of the feedback. For example, the soil moisture content was prescribed at 1% over much North America in one such experiment (Oglesby 1991).

Precipitation Recycling: Until recently, precipitation recycling was believed to be an important component of the soil moisture-rainfall feedback (Brubaker et al. 1993; Eltahir and Bras 1996). The reasoning behind this idea is as follows. Evapotranspiration (ET) and horizontal advection are the two sources of water in the atmosphere over land, and therefore they are the sources of precipitation. Because high soil moisture enhances ET, the amount of water available for precipitation should increase when soils are wet. However, recent studies of precipitation recycling show that only ~10% of the water evaporated from regions ~1000 km x 1000 km in area precipitate in that region (Trenberth 1998). In addition, the magnitude of recycling is less when smaller regions are considered (Eltahir and Bras 1996; Trenberth 1998), whereas soil moisture and surface flux anomalies are greatest over relatively small areas. Therefore, it appears that precipitation recycling probably does not contribute greatly to feedbacks between soil moisture and rainfall.

Boundary Layer Effects: If precipitation recycling provides only a weak link between soil moisture and rainfall, then what mechanisms could actually be important? A feedback may result from the influence that surface-atmosphere fluxes have on the thermodynamic state of the atmospheric boundary layer (BL), and therefore the likelihood for convective precipitation (Betts and Ball 1998; Eltahir 1998; Trenberth 1998). Betts and Ball (1988) and Eltahir (1998) used data from FIFE to examine the relationship between soil moisture and surface-atmosphere fluxes. They also examined the relationship between soil moisture and the thermodynamic state of the BL, as represented by data collected from the surface layer. Their BL analysis was based on the assumption that the conditions in the surface layer were representative of those in the mixed layer, which may not be valid if the land surface is disorganized (Hipps et al. 1994). The data represent typical conditions during the growing seasons of 1987-1989, as measured by up to ~20 micrometeorology stations deployed in a 15 x 15 km area of tall grass in Kansas.

The surface energy balance, which is a basic component of the proposed feedback, can be simplified to include net radiation (R_n), ground heat flux (G), latent heat flux (LH), and sensible heat flux (H).

$$R_n - G = LH + H = Q_a$$

The available energy (Q_a), or the energy transferred from the land surface to the atmosphere, is equal to the net radiation absorbed by the surface minus the energy transferred into the ground.

We now describe the feedback between wet soil and rainfall proposed by Betts and Ball (1998). The effects of dry soil would be opposite in sign.

Wet soil results in a relatively high evaporative fraction (EF). The EF is the component of available energy (net radiation minus ground heat flux) transported away from the surface in the form of latent heat, or LH/(LH+H).

A high evaporative fraction yields a lower lifting condensation level (LCL) or cloud base. A high EF implies limited sensible heat transfer, and therefore limited entrainment at the top of the BL. The net result is a shallower boundary layer (lower cloud base or LCL).

A high evaporative fraction and low LCL results in higher boundary layer θ_e (equivalent potential temperature) **or moist static energy**. The surface available energy (R_n-G) does not vary with soil moisture because the changes in R_n and G driven by soil moisture variations tend to cancel. Because higher soil moisture yields a lower LCL, the same amount of energy is "concentrated" within a shallower boundary layer, thereby raising θ_e. In addition, there is less entrainment of low θ_e air from the free atmosphere that tends to decrease energy within the BL. The first three components of the feedback were confirmed using FIFE data.

Higher θ_e and lower LCL favors convective precipitation. This BL-precipitation link is based on relationships between BL conditions and the probability of precipitation (e.g., Eltahir and Pal 1996) and thermodynamics of atmospheric convection, not on data collected during FIFE.

A key element to the proposed feedback is that soil moisture anomalies and the attendant surface fluxes must be consistent on a spatial scale that is large enough so that BL turbulence does not simply average everything out. Shuttleworth (1988) referred to a landscape that was spatially coherent enough to impact the BL as 'organized', and stated that the threshold lengthscale differentiating organized and disorganized surfaces is ~10 km. Andre et al. (1990) also suggested ~10 km was the likely threshold, based on results from the HAPEX-MOBILHY project. Betts and Ball (1998) wrote that the threshold lengthscale is ~200 km, as this is the distance air typically travels on the timescale over which the BL evolves (~12 hours). Results from modeling studies show that anomalous land surface conditions over several 10's of km yield mesoscale circulations (e.g., Segal 1988). We will assume that ~10 km is the minimum scale at which fluxes must be consistent for the landscape to be 'organized'. If soil moisture and surface fluxes are not coherent at this scale, then they will also be disorganized at the larger lengthscale suggested by Betts and Ball (1998) or other studies.

Net Radiation Effects: Using the same data, Eltahir (1998) proposed a mechanism to explain the soil moisture-rainfall feedback that was similar to Betts and Ball (1998) except for one major difference. He hypothesized that high (low) soil moisture increases (decreases) the net radiation absorbed by the land surface, thereby increasing (decreasing) the moist static energy (or θ_e) transported into the BL. The enhanced BL energy increases the likelihood of convective precipitation, similar to the concentration of energy caused by a shallow boundary layer (Betts and Ball 1998). Eltahir (1998) proposed that the net radiation effect was the key element of the feedback, which was supported by model simulations (Zheng and Eltahir 1998). The dependence of net radiation on soil moisture was based on the following reasoning.

- Wet soil decreases the surface albedo, and therefore increases the net shortwave radiation.
- Wet soil increases the evaporative fraction (or reduces the Bowen Ratio), lowering the surface temperature and thereby decreasing the longwave radiation emitted by the surface.

Eltahir also suggested that vegetation growth stimulated by wet soil would enhance the net radiation feedback. In the FIFE study area, the change in net radiation between dry and wet soils was only ~10 Wm^2, and was primarily the result of a decrease in longwave emitted by the surface. Regardless of the importance of the net radiation feedback, it is critical that soil moisture anomalies and attendant fluxes are spatially homogenous for the land surface state to impact strongly the boundary layer.

1.2 Research Objectives

The objective of this research was to test the following hypothesis regarding the nature of the soil moisture-rainfall feedback in semiarid regions.

- **There is a dramatic land surface response to precipitation events and the associated rise in soil moisture**. Wet soil increases the evaporative fraction, as observed at the FIFE site. Wet soil also increases R_n, although the variations may be negligible (~10 W m^{-2}) as observed at the FIFE site.

- **The response to rainfall events is limited in duration.** The hydrologic memory of the land surface is not limited by the storage capacity of the root zone. Instead, it is limited by the actual amount of water held as soil moisture. The amount of precipitation that accumulates during a single event is large relative to the water stored in the soil (White et al. 1997). Therefore, the spatial variability of soil moisture is similar to the spatial variability of rainfall accumulating during some event, which is typically high during the monsoon season. If this hypothesis is correct, then the land surface is 'disorganized' with respect to soil moisture anomalies and surface fluxes due to the combination of minimal hydrologic persistence and the limited spatial extent of individual convective precipitation events.

- **Heterogeneous vegetation contributes relatively little to the spatial variability of soil moisture and surface fluxes.** Even though the vegetation varies substantially over short distances in some semiarid environments, such as the Sevilleta LTER (Figure 1), this does not strongly influence patterns of soil moisture and surface fluxes. The effects of transient soil moisture anomalies yield greater changes in surface fluxes than differences in vegetation. In other words, the difference between a dry and wet grass site is greater than the difference between a grass and shrub site, if both sites are either dry or wet. However, the effects of vegetation may be greater on the seasonal timescale, when the importance of contrasting root zone depth yields site-to-site differences in fluxes.

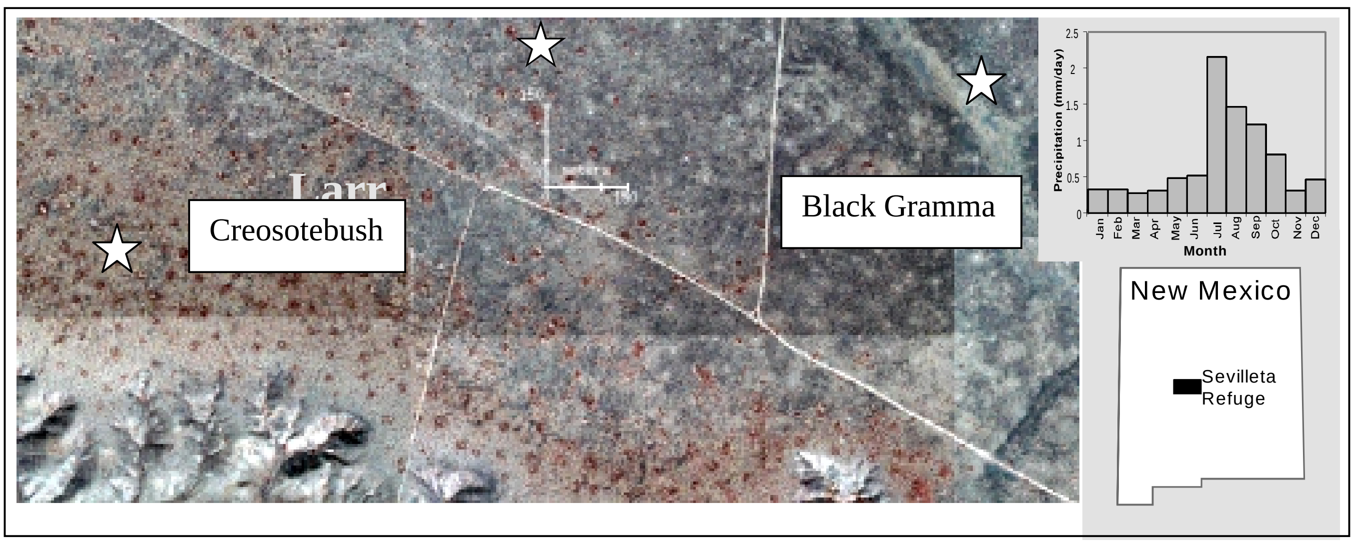

Figure 1. 1-m resolution ADAR image of the "5-points" study area, showing the eastern half of the Sevilleta LTER in central N.M. (inset at right). *Larrea* appears red, Black Grama appears black, and bare ground appears white in this image. The white star shows the locations of the drought plots – directly at the shrub-grass biome transition. Monthly precipitation from Socorro, NM (20 km south of the Sevilleta) is shown at the top right.

2. Study Area

The research discussed in this report was completed in the Sevilleta National Wildlife Refuge in central New Mexico (Figure 1). Annual precipitation is ~250 mm throughout most of the Sevilleta and generally increases with elevation. Roughly half of the annual precipitation accumulates during the summer monsoon season (Figure 1, top right). Our study was conducted in the northeast portion of the Sevilleta, referred to as the "5-points" study area. The slope throughout this area is between 1 and 2%.

We measured the surface water and energy balance at three stations spanning the shrub-grass ecotone at the Sevilleta. The Chihuahuan Desert biome abuts the Great Plains Grassland biome in the Sevilleta, representing the northern edge of shrub encroachment into the grasslands (Figure 1). The narrow and distinct shrub-grass ecotone found at the Sevilleta is integral to our objectives – the transition from nearly 100% shrubs to nearly 100% grass occurs over a distance of ~0.5 km. South of the ecotone, the landscape is nearly entirely covered by the shrub *Larrea tridentata* (creosotebush) (Figure 2). North of the ecotone, the dominant grass is *Bouteloua eriopoda* (black grama) with secondary contributions from *Bouteloua* gracilis (blue grama), *Hilaria sp*., *Sporobolus sp*. , *Guttierezia sarothrae*.

There are three stations studied here (Figure 1). The shrub and grass stations are amidst monospecific stands of creosotebush and black gramma, respectively (Figure 2). The vegetation is uniform for at least 100 m around both stations. A third station is located in a mixed grass-shrub environment, directly at the ecotone (Figure 3). The mixed vegetation is of uniform proportion for several hundred meters around this station, except for from the north.

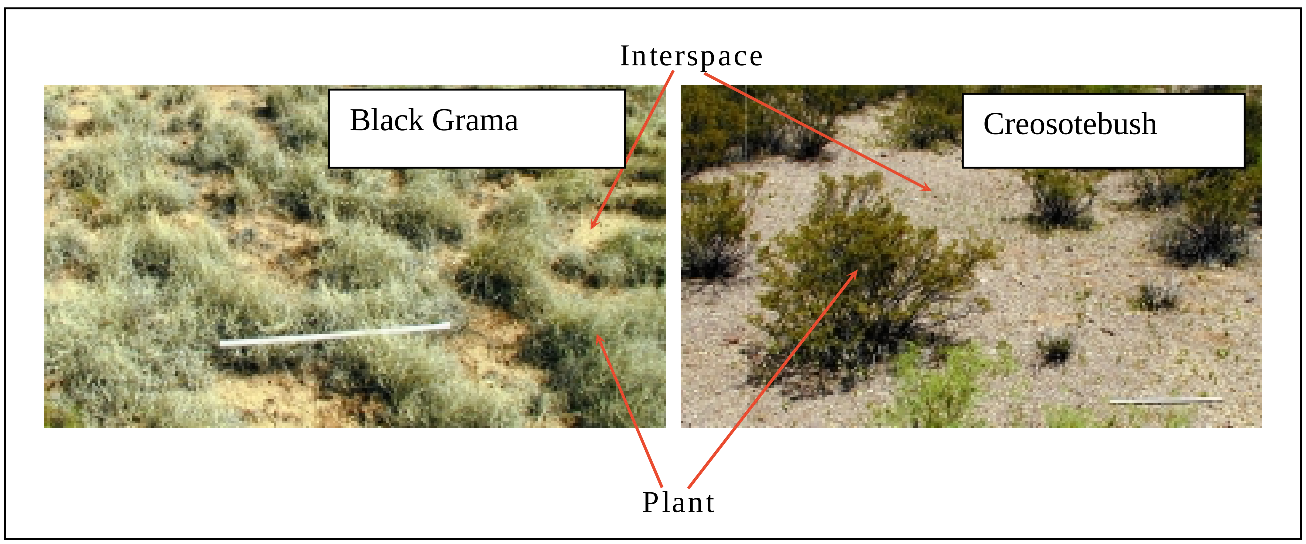

Figure 2. Examples of typical Black Grama grassland (left) and creosote bush shrubland (right) at the Sevilleta LTER. White bar in both photos is 1 m long (bottom right in shrubland). The grassland canopy is composed of grass clusters ~25 cm in horizontal extent, with interspaces of similar size. Plant and interspace dimensions are roughly an order of magnitude larger in shrubland.

3. Methods

Turbulent Fluxes: Fluxes of sensible and latent heat (and therefore ET) are estimated using two different methods. The eddy covariance method is used to calculate sensible and latent heat at the mixed site. Temperature is measured at 10 Hz with a 0.0005” fine wire thermocouple. Vapor density is also measured at 10 Hz with a Krypton hygrometer. A 3-D sonic anemometer is used to measure wind velocity in three orthogonal directions, also at 10 Hz. The covariance between vertical wind velocity and temperature is then used to calculate sensible heat, and between vertical wind velocity and vapor density for latent heat. The eddy covariance method provides sensible and latent heat measurements over a horizontal distance of ~100 times the instrument height, or 250 m in our case.

At the grass and shrub sites, the turbulent fluxes are estimated using the Bowen Ratio Energy Balance method (BREB). Vertical temperature and vapor pressure gradients are measured over a 2 m span (Figure 4). The lower probe is placed at a height of 1.25 times that of the canopy height. This is ~60 cm in the grassland and 1.5 m in the shrubland. The BREB method also requires measurements of net radiation and ground heat flux, as the difference between these two quantities is the available energy, Q, that is partitioned between sensible and latent heating. The BREB method provides sensible and latent heat estimates for an area upwind that is roughly 25-50 x average probe height – equal to ~50 to 100 m for our setups (Stannard, 1997).

At FIFE and in environments similar to the Sevilleta, BREB and eddy correlation

Figure 3. Mixed grass-shrub site located directly at the ecotone. The mixed vegetation shown here extends for several hundred meters to the south of the station.

measurements are typically similar (within measurement error) when the humidity gradient is great enough to be resolved by the BREB method (Smith et al. 1992; Unland et al. 1996). Differences may exist under certain situations when topography is complex (Fritschen et al. 1992), but our Sevilleta sites are nearly flat over a distance of several hundred meters. Therefore, combining BREB and eddy covariance measurements should only introduce minor inconsistencies into our site-to-site flux comparisons.

Radiation: Net radiation is measured at all three sites using REBS net radiometers. The four components of the surface radiation budget (up and down short and longwave radiation) are measured at the grass and shrub sites, using REBS double-sided pyranometers and total hemispheric radiometers. The land surface is very heterogeneous at the 10-100 m scale in the shrub environment, compared to adjacent grassland. So, measurements of net radiation near the tower are not necessarily representative of the area sampled by the BREB gradient measurements (~100 m). We completed net radiation surveys at each site to evaluate the effects of spatial heterogeneity. The net radiation measured near the station was within 1-2% of the average from an area around each site.

Ground heat flux: At each site, ground heat flux is measured continuously at two locations, using soil heat flux plates and measurements of soil temperature. The heat flux plates are placed at a depth of 5 cm beneath the surface, beneath both plant canopies and interspaces (Figure 2).

Soil Moisture: At each site, soil moisture profiles were monitored at the same two patches where heat flux is measured. Campbell Scientific water content reflectometers (WCR) were

Figure 4. Grassland and shrubland micrometeorological stations. The temperature and humidity probes are on the left side of the photo in the grassland and at the center in the shrubland. The radiometers (net radiation, shortwave, and longwave) are on the right side of both photos. Ground heat flux and soil moisture are measured uphill of both stations, under both plant canopy and interspace.

used to monitor moisture content at the following depths: 2.5, 12.5, and 22.5 cm. The WCR provide continuous measurements of volumetric soil moisture content (VWC) based on the time domain reflectometry method. We did not calibrate the WCR specifically for soils in the Sevilleta.

4. Results

We now present results from the three stations discussed in sections 2 and 3. All measurements are from the 2000 monsoon season. The period of record for most variables is June 1 through November 1. To assess the influence of soil moisture on the different components of the surface energy balance (SEB), we compare data from days with dry and wet soil. Day of Year 233 is chosen to represent wet conditions. It was a cloud-free day following a period with substantial rainfall (Figure 5). We use Day of Year 254 to assess dry conditions. It is also a cloud-free day, but follows a dry period that was two weeks long.

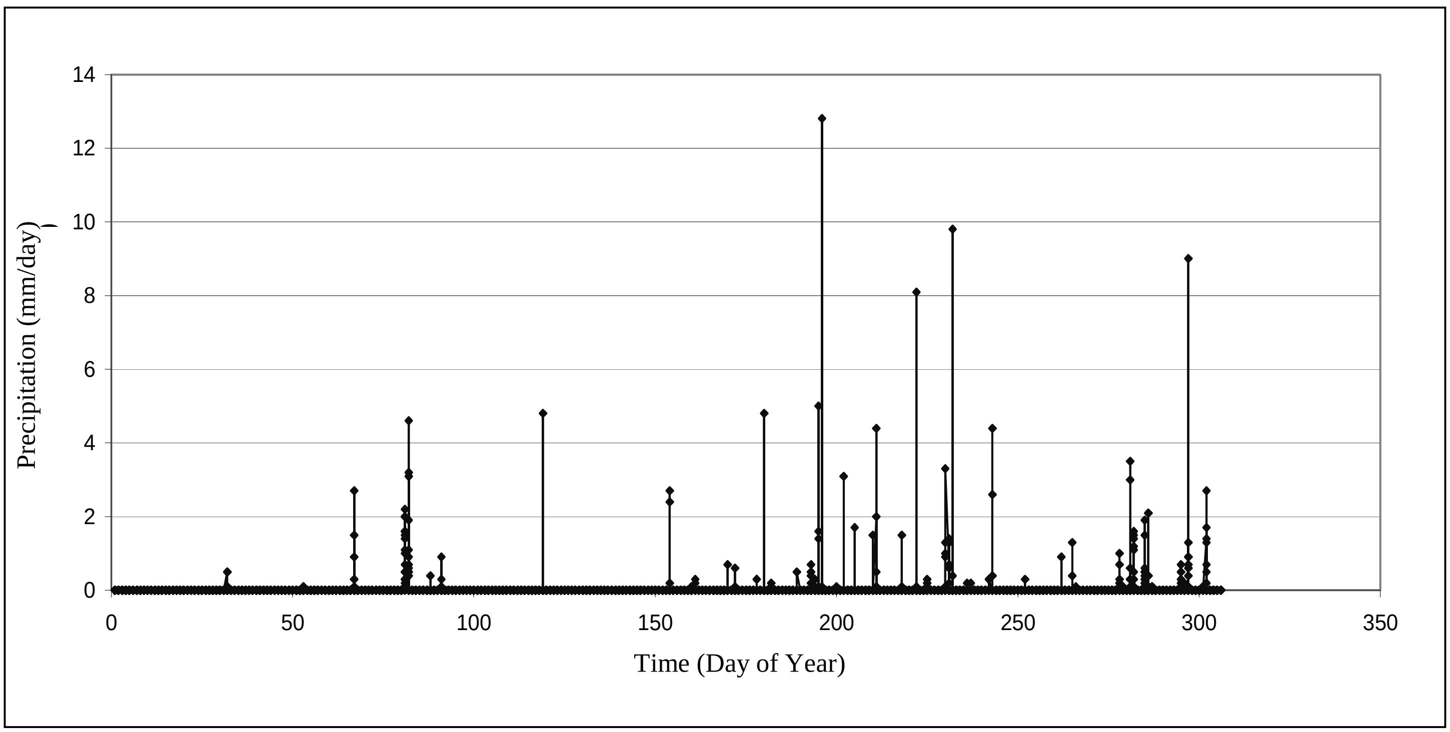

Figure 5. Precipitation record from the 5-points meteorological station, ~150 m east of the mixed site.

4.1 Magnitude of the response to rainfall

4.1.1 Soil moisture and evaporative fraction

First we compare the diurnal cycle of the surface energy balance between days with dry and wet soil. The grassland surface energy balance differs substantially between the dry and wet day (Figure 6). Net radiation follows a sine curve on each day caused by the daily cycle of incident shortwave radiation, as both days are cloud free. Net radiation is lower on the dry day (JD 254), at least partly because this day is later in the summer. We investigate the direct effects of soil moisture on net radiation in the following section evaporative fraction. The ground heat flux is also similar on both days, although perhaps reaching its maximum value earlier in the day when soil is dry. A large difference exists between the latent and sensible heat fluxes on these two days. Roughly half of the available energy is returned to the atmosphere via latent heating on the wet day, with a maximum value at noon of ~350 W m^{-2}. In contrast, the maximum latent heat value on the dry day is only 50 W m^{-2}. The Bowen ratio (i.e., the ratio of sensible heat to latent heat) is much lower on the wet day because there is more soil moisture available for both bare

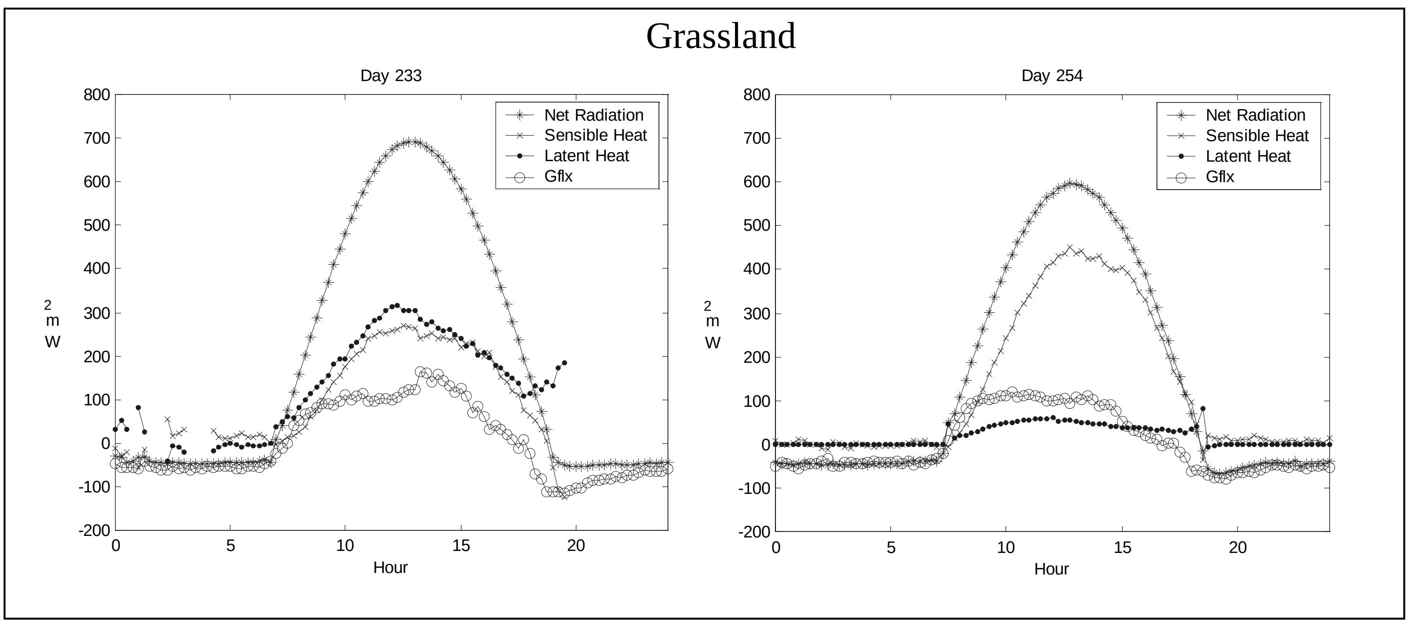

Figure 6. Components of the SEB at the grassland site. Left side shows a wet day (JD 233) and right side shows a dry day (JD 254). Hours from midnight are plotted on the x-axis, with time shifted one hour forward from the solar cycle due to daylight savings time.

soil evaporation and transpiration than when the soil is dry. The Bowen ratio on the wet and dry days is ~0.6 and ~8, respectively.

The wet-dry SEB differences at the mixed and shrub-dominated sites are similar to those observed in the grassland (Figures 7 and 8). However, several notable differences do exist. First, on the dry day, the sensible heat flux reaches a maximum value at ~4 P.M. at both the mixed and shrub sites. In contrast, the maximum sensible heat flux is observed around noon in the grassland. Second, on the wet day, the latent heat flux at the shrub site reaches a maximum

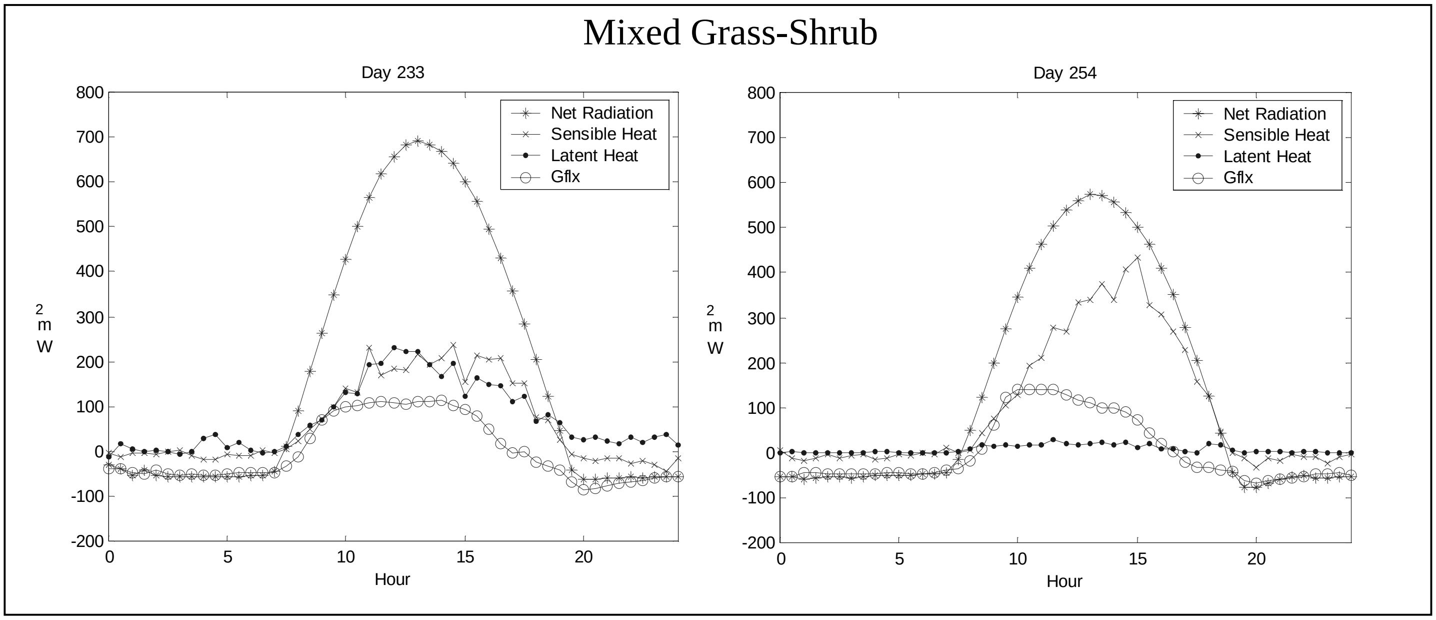

Figure 7. Same as Figure 6 but at the mixed grass-shrub site.

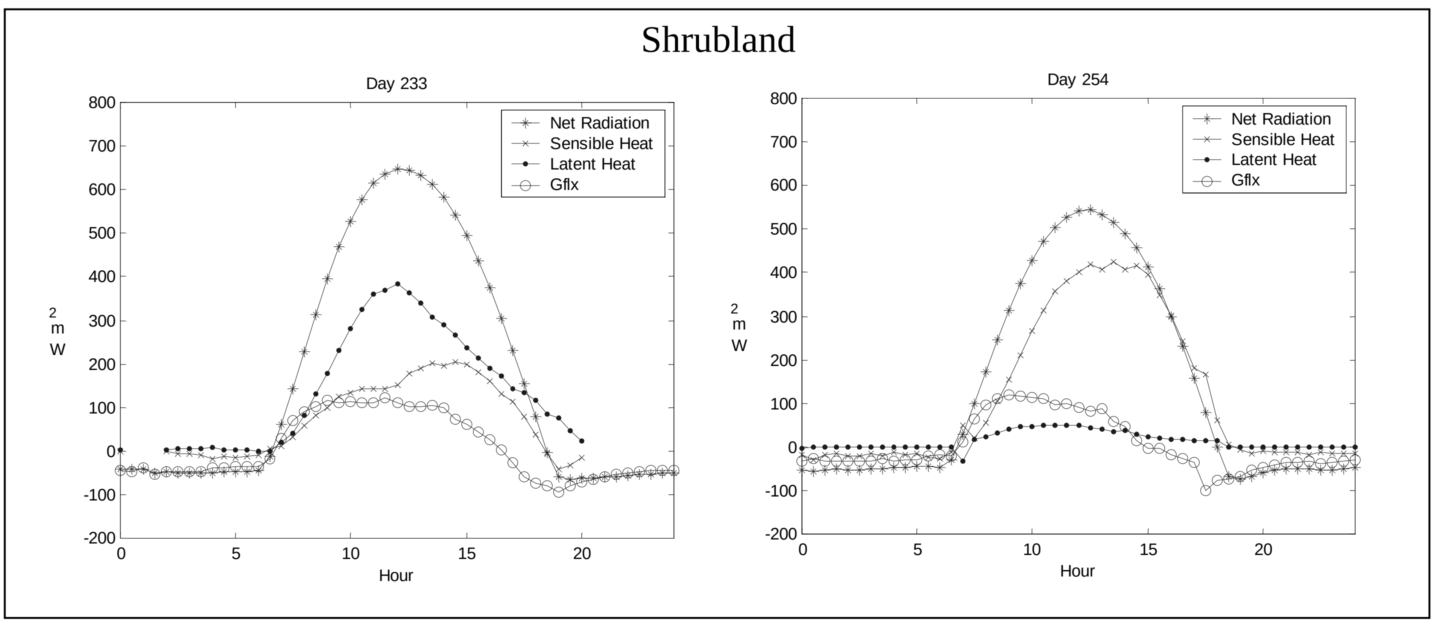

Figure 8. Same as Figure 6 but at the shrub site.

at ~ 11 A.M. and decreases steadily afterwards. In addition, this peak is much greater than the maximum sensible heat flux throughout the day.

There is one other notable difference between the daily cycle of the SEB between the three sites. At the mixed site, the sum of the latent and sensible heat fluxes is less than that observed in the grass or shrubland, on both the dry and wet days. For example, the sum at noon is only 400 W m^{-2}, compared to ~550 W m^{-2} at the other sites. We expect that this represents a problem with the eddy correlation measurements at the mixed site because the sum of the latent and sensible heat fluxes appears to be ~100 W m^{-2} less than the available energy (i.e., the difference between net radiation and the ground heat flux). This problem is typical when using the eddy covariance method. A likely cause for the underestimate of turbulent fluxes is that both latent and sensible heats are transported in eddies that are too small and large to be detected in the system configuration used here.

4.1.2 Evaporative Fraction

A convenient way to assess the intensity of the SEB response to rainfall events and the attendant rise in soil moisture is to calculate the evaporative fraction (EF). EF is the fraction of available energy transferred away from the surface via latent heating, and is equal to the ratio of latent heat to available energy. We plot the EF during daylight hours measured at each station on the dry (JD 233) and wet (JD 254) days. Three features are important (Figure 9). First, the EF is relatively constant between 9 A.M. and 3 P.M. on both dry and wet days at all three sites, with the exception of the wet day at the shrub site. Second, EF on dry days is similar across the three sites, between 0.05 and 0.15, and tends to decrease throughout the morning. Third, the wet day EF is similar at the grass and mixed sites (~0.5) but is somewhat higher at the shrub site, particularly around 11 A.M. (EF = 0.7).

So far our analysis has been based on only two days with very different amounts of soil water. We generalize these results by comparing how EF varies with soil moisture content at the three sites (Figure 10). Overall, the EF-VWC relationship appears similar across the study area: First, EF increases with water content roughly linear, with a rate of ~6 $\%^{-1}$. And second, there is substantial scatter. For example, there is a cluster of points at high volumetric water content but relatively low EF in each plot, which represent points from late October, 2000. Relatively higher EF values under wet conditions are not always observed at the shrub site, as seen on day 233.

There appears to be more variations in EF at a particular volumetric water content (VWC) at the mixed and shrub sites than at the grassland site.

These results demonstrate that the intensity of the SEB response to rainfall, at least in terms of changes in partitioning of available energy between sensible and latent heat, is relatively uniform across the grass-shrub ecotone. In addition, the EF response observed in these two semiarid environments is similar to that found in grasslands in more humid environments (Figure

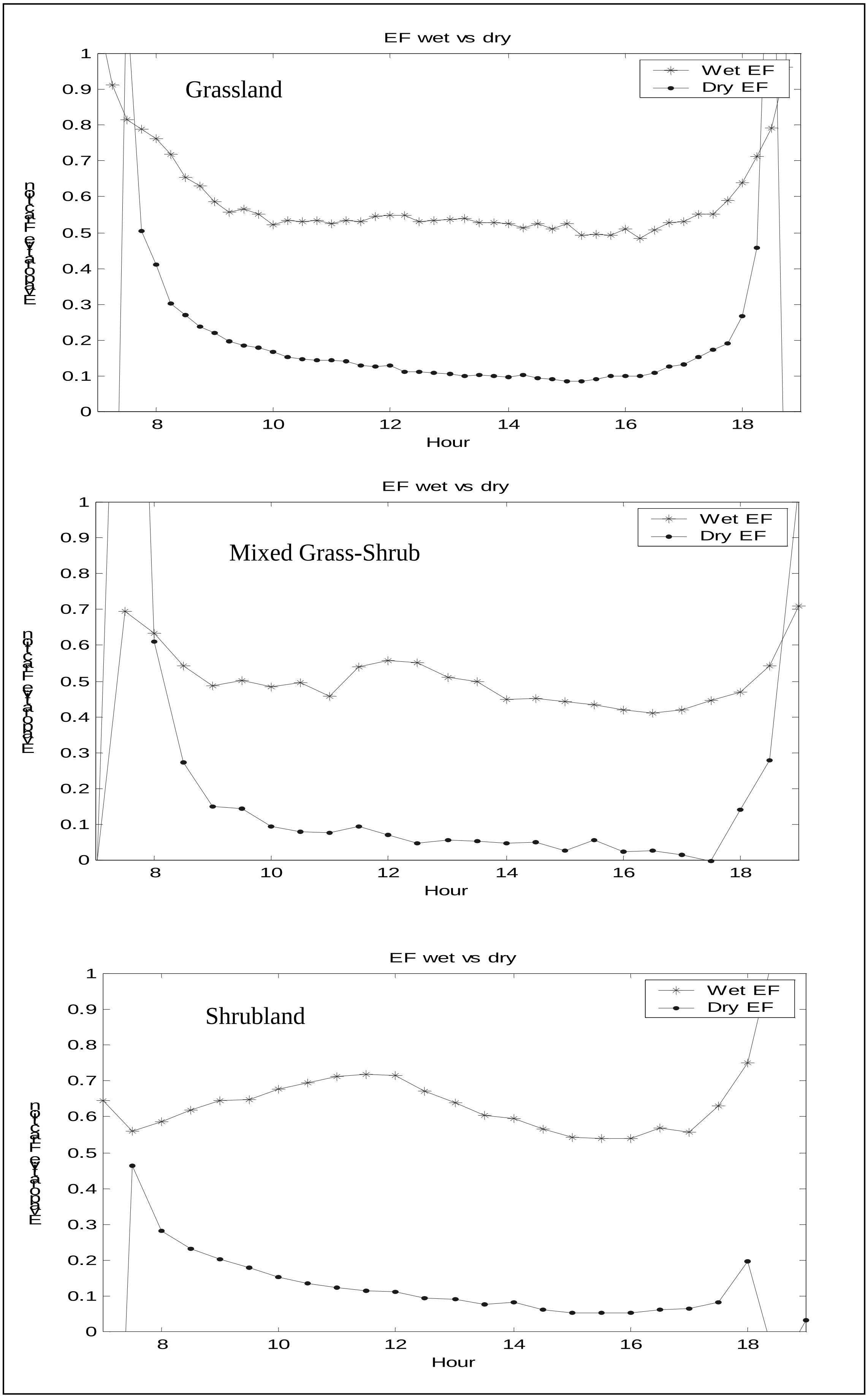

Figure 9. EF plotted during daylight hours at the three stations on both the wet (JD 233) and dry (JD 254) days. Top is grass, middle is mixed, and bottom is shrubland.

11). Two differences exist between our results and those from the Konza Prairie in Kansas: (1) the dry-wet EF differences is less in the Konza; and (2) EF on wet days is higher in the Konza than the Sevilleta by ~0.2.

4.1.3 Net radiation

We now test Eltahir's (1998) soil moisture-net radiation feedback hypothesis: wet soil yields higher net radiation, and therefore total energy transfer from the land surface to the atmosphere. Betts and Ball (1998) suggest that although net radiation may increase when soil is wet, the concomitant increase in ground heat flux yields no net change in available energy.

We remove the effects of the seasonal cycle and clouds by normalizing available energy, net radiation, and ground heat flux by incident shortwave radiation. Because shortwave radiation is only measured at the grass and shrub sites, we do not present results for the mixed grass-shrub environment.

In the grassland, net radiation is generally higher when the soil is wet (Figure 12). The points with the highest normalized net radiation define a roughly linear relationship. In contrast, the relationship is less clear for points with lower normalized values. These points represent times when shortwave radiation is reduced by clouds. Ground heat flux is also higher when the soil is wet, but the change is less dramatic. Again, observations under cloudy conditions introduce a fair bit of scatter for the lower points. Because the change in ground heat flux with increasing soil moisture is less than that for net radiation, available energy shows a modest increase for wet soils. The change in shortwave normalized available energy associated with an increase in VWC from 10 to 15% is 0.1. This converts to a 100 W m^{-2} change in available energy for midsummer values of shortwave radiation.

A similar relationship between net radiation, ground heat flux, and available energy exists in the shrubland (Figure 13). However, the relationship is somewhat less clear for each variable than in the grassland. Again, we estimate that an increase of VWC from 10 to 15% yields an increase in available energy of ~100 W m^{-2}. In both cases, variations associated with the seasonal cycle or other factors introduce noise into the relationship. These factors need to be addressed before a more quantitative test of Eltahir's (1998) hypothesis is possible.

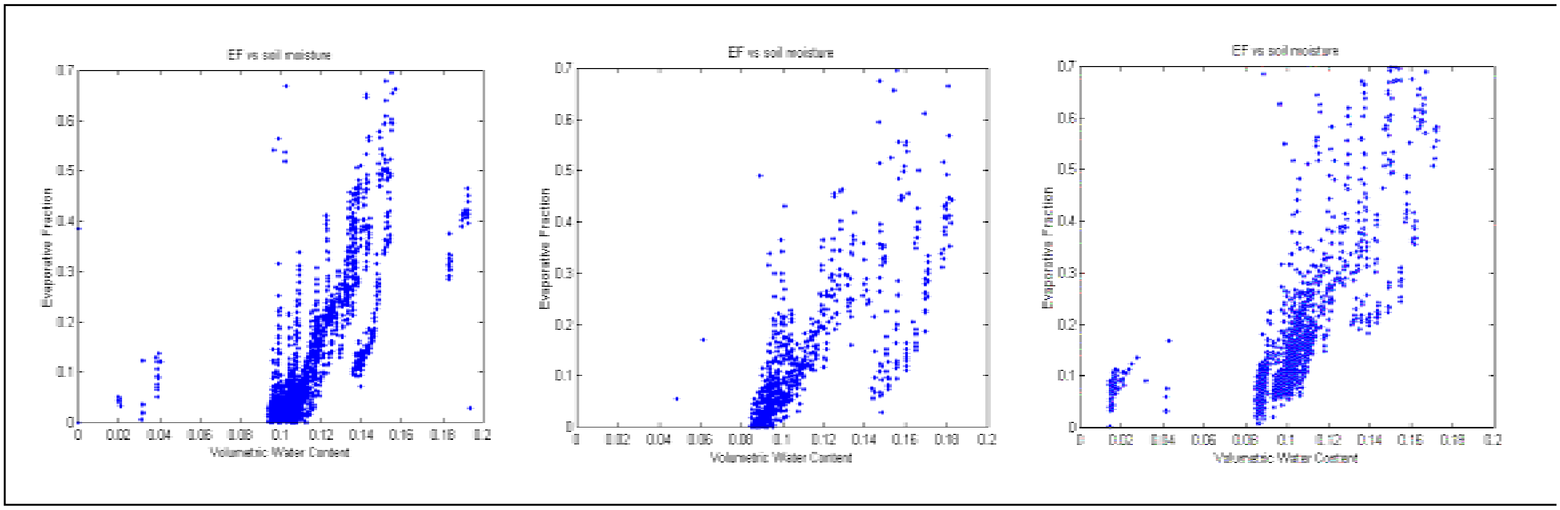

Figure 10. Evaporative fraction versus volumetric soil moisture content at the grass (left), mixed (center), and shrub sites (right). EF values between 10 A.M. and 2 P.M only are plotted here.

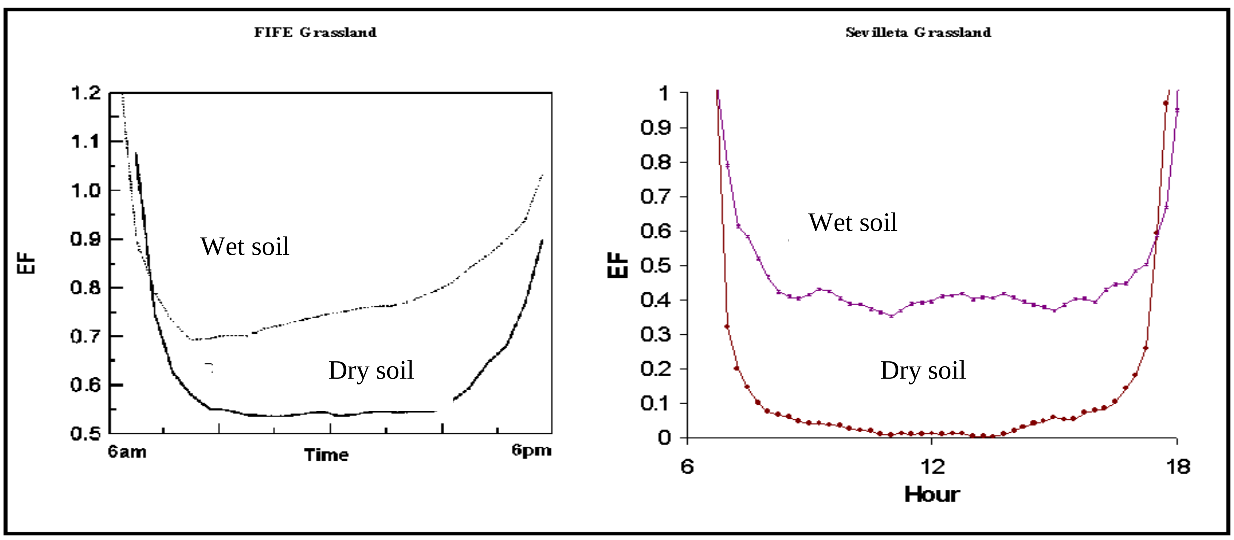

Figure 11: Left: Diurnal cycle of evaporative fraction (EF) from the Konza prairie in Kansas. Wet and dry soil lines represent averages over many days. Right: Diurnal cycle of evaporative fraction from Sevilleta grassland. Wet and dry soil lines represent values from a single wet and dry day during the 1999 monsoon season.

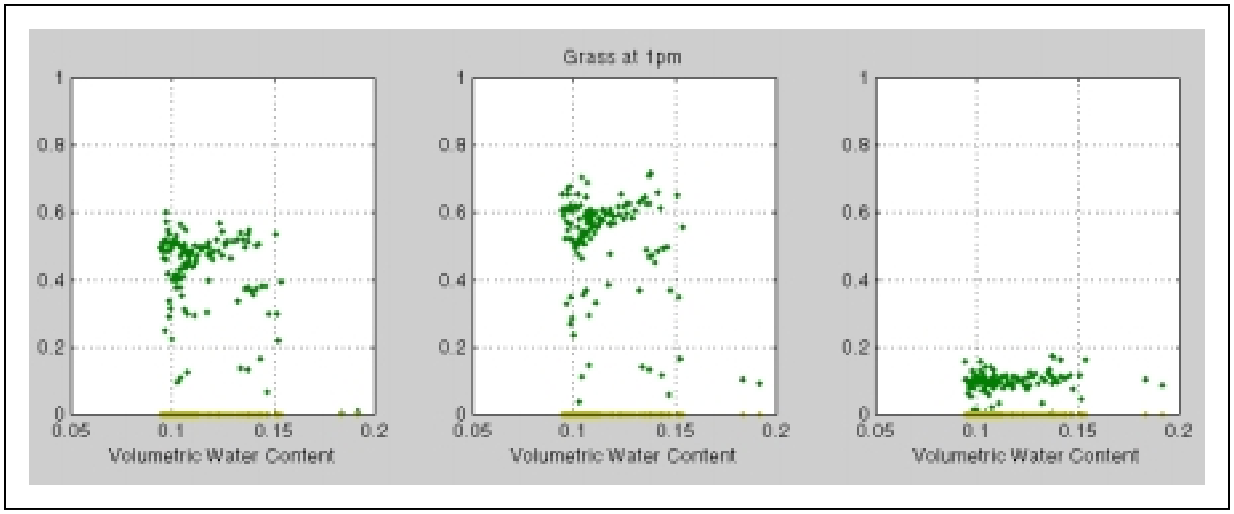

Figure 12. **Grassland** available energy (left), net radiation (center), and ground heat flux (right) as a function of volumetric water content at 1 PM local daylight time, roughly equal to solar noon at this longitude. All are normalized by incident shortwave radiation to remove effects of seasonal cycle and clouds.

One possible source of the increase in net radiation when soil is wet is that the albedo of wet soil is typically lower than that of dry soil. Albedo is the fraction of incident shortwave radiation that is reflected. Changes in albedo associated with vegetation state may also be important. A lower albedo increases net radiation because a larger fraction of the incident shortwave radiation is absorbed by the surface.

We plot variations of albedo with volumetric water content in Figure 14. Several features

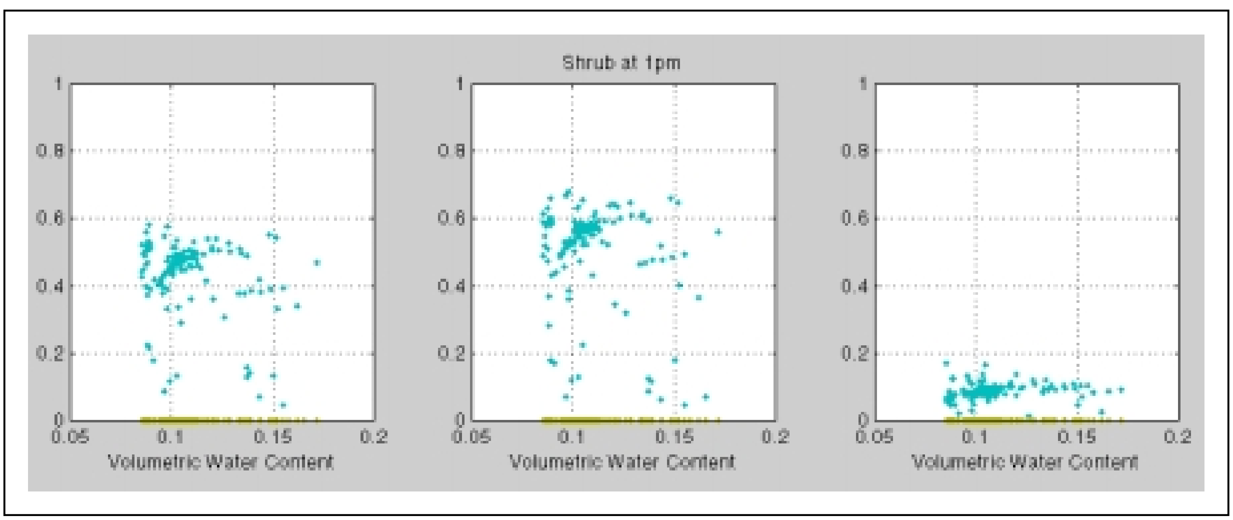

Figure 13. Available energy (left), net radiation (center), and ground heat flux (right) as a function of volumetric water content in **shrubland** at 1 PM local daylight time, roughly equal to solar noon at this longitude. All are normalized by incident shortwave radiation to remove effects of seasonal cycle and clouds.

are important. First, albedo is usually higher in the shrubland than in the grassland, by several percent. There are two reasons why this is the case: (1) there is more bare soil in the shrubland; and (2) the bare soil is more reflective in the shrubland. Differences in vegetation albedo may also be important. Second, albedo is higher when soil is dry in both the grass and shrubland, although there are substantial variations in albedo under these conditions. Third, the decrease in albedo with increasing VWC appears to be greater in the grassland. An increase in VWC from 10 to 15% appears to result in a decrease in albedo of 5%. For midsummer conditions, this is equivalent to an increase in shortwave radiation absorbed of ~50 W m^{-2}, thus explaining roughly half of the sensitivity of available energy and net radiation to changes in VWC (Figures 12 and 13). The remaining portion of changes in net radiation associated with increases in VWC is likely caused by the decrease in surface temperature, and therefore the reduction in longwave radiation emitted, observed when the soil is wet.

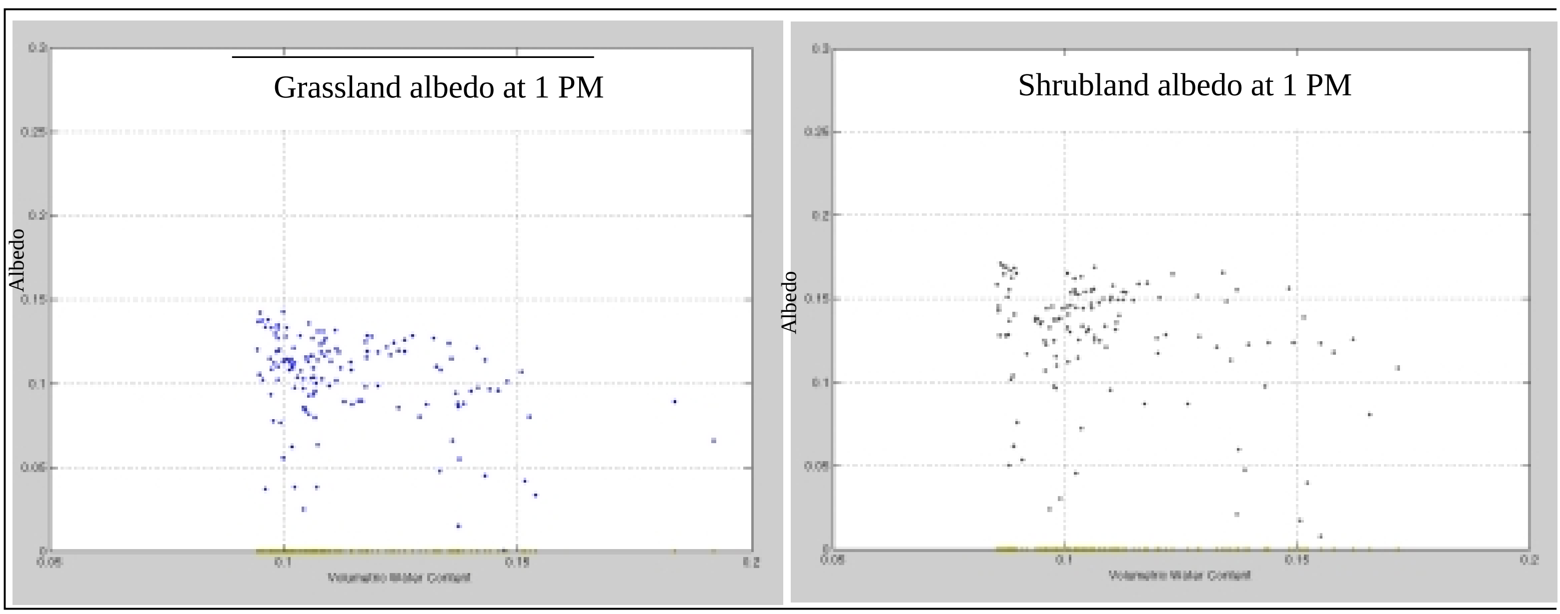

Figure 14. Albedo (y-axis) versus volumetric water content at grass (left) and shrub (right) sites at 1 PM, which is roughly solar noon at this longitude.

4.2 Persistence of hydrologic anomalies

We now investigate the persistence of anomalous SEB conditions associated with rainfall events and the associated rise, and subsequent decay, of soil moisture. The basic question is: How long does the SEB reflect wet conditions following rainfall events? The greater the persistence, the higher the probability for feedbacks between soil moisture and rainfall. The persistence depends on several factors: (1) the magnitude of the rainfall event; (2) the pre-existing soil moisture state; (3) how rapidly water is removed from the root zone, via the combination of bare soil evaporation and transpiration; and (4) the amount of time until the next rainfall event.

The 2000 season can be divided into three separate stages. A dry, pre-monsoon interval persisted until ~JD 200 (July 20). (Figure 15). Several small rainfall events yielded short-duration increases in ET with peaks of ~1.5 mm d^{-1}. Roughly 100 mm of rainfall accumulated during the next 50 days (JD 200-250), which was effectively the 2000 monsoon season. A sequence of six rainfall events yielding 10-mm or more of precipitation occurred during this interval. Maximum ET following these events reached ~ 4 mm d^{-1}, and the minimum daily ET did not fall below 1 mm d^{-1}. The final interval began roughly on JD 260 (mid-September) and lasted throughout the end of the record. There were several 10 mm storms in October. ET was relatively low (~1 mm d^{-1}) except following these events.

The following observations pertain to the record at all three stations. First, during the first and third periods throughout the season, the wet conditions did not persist from storm to storm. ET dropped to 0.5 mm d^{-1} or lower following each rainfall event. Both bare soil evaporation and transpiration are lower during these intervals than during the peak of the summer. Therefore, the lack of persistence appears to be dominated by the combination of: (1) low magnitude rainfall events; and (2) long duration between events. Second, during the wetter period in the middle of the summer, ET remained relatively high between events, rarely falling below ~1 mm d^{-1}. Although there is a notable difference with the previous and subsequent intervals, ET still decreased to only ~25% from the maximum values between each rainfall event. Even though rainfall events were larger and more frequent, wet conditions generally did not persist from event to event. Higher rates of ET, particularly the bare soil component, contribute to the lack of persistence during this interval. Third, the decline in ET following rain events appears to be exponential, particularly at the shrub and mixed sites. The dry-down following the rainfall event on Day of Year 242 is a clear example of this relationship.

There is a substantial difference between the record at the mixed grass-shrub site and those observed in the grass or shrub areas. At the mixed site, the peaks following rain events are not as large and the troughs after several days of evaporation are lower. We expect that this difference is the result of instrumentation rather than site-to-site differences, as discussed above.

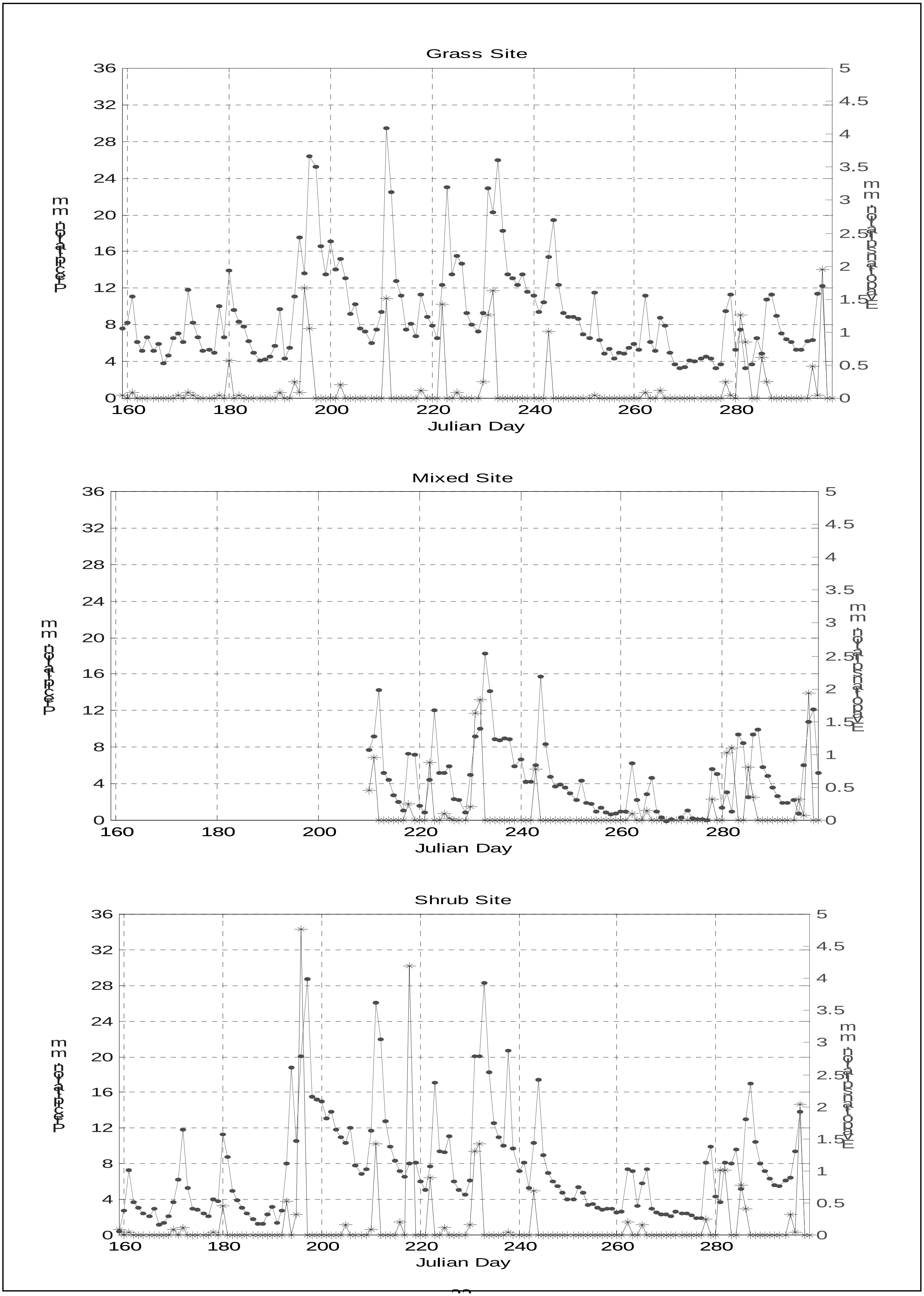

Figure 15. Records of daily precipitation and evapotranspiration from the grass (top), mixed (middle), and shrub (bottom) sites.

5. Summary

Our data analysis yields four major results concerning the nature of soil moisture-rainfall feedbacks in semiarid regions.

1) **The SEB response to rainfall inputs is dramatic:** Changes in the evaporative fraction (EF) resulting from wet versus dry soil moisture conditions are dramatic. This result applies to the grassland, shrubland, and mixed grass-shrub environments studied here. When the soil is dry, the evaporative fraction is typically 0.1, demonstrating that only 10% of the energy transferred from the surface to the atmosphere is via latent heating. In contrast, the evaporative fraction is ~0.5 when the soil is wet. Rainfall-soil moisture feedbacks are hypothesized to be important in the Midwest, where soil moisture driven variations in EF are only half as large as found in the Sevilleta (Betts and Ball 1998). This demonstrates that the SEB response to rainfall, at least in terms of latent heating, is substantial and could yield a feedback with the atmosphere.

2) **Net radiation-soil moisture relationships:** Net radiation and available energy both increase when the soil is wet, in both the grass and shrub environments. The ground heat flux is enhanced when the soil is wet, which decreases the intensity of the net radiation and available energy response. However, changes in available energy are still substantial – a volumetric water content change of ~5% yields an increase of 50 W m^{-2}. If this result is accurate, then the soil moisture-net radiation feedback proposed by Eltahir (1998) would contribute to soil moisture-rainfall feedbacks in semiarid regions such as the Sevilleta. More work is needed to test this result, including: (1) refining the relationship between ground heat flux and volumetric water content; and (2) improving the method for removing the effects of seasonal cycle and clouds on normalized available energy or net radiation.

3) **Hydrologic persistence is limited**: The intense EF and net radiation responses to rainfall events and the attendant rise in soil moisture is short lived, at all locations across the ecotone. During the peak of the monsoon season, EF drops to only 25% of the maximum observed values before the next rainfall event occurs. The transience is even greater before and after the peak

monsoon season. The several day persistence found here differs dramatically from the monthly persistence observed in the Midwest. This result has the following implication for the likelihood and importance of a soil moisture-rainfall feedback in semiarid regions such as the Sevilleta. The high latent heating and net radiation caused by wet soil can only increase the likelihood of precipitation for several days following a rainfall event. Therefore, a soil-moisture rainfall feedback will only exist if the atmospheric conditions conducive for convective precipitation occur within several days after a rainfall event.

4) **Plant type does not influence the soil moisture-rainfall feedback:** The evaporative fraction and net radiation response to rainfall is nearly identical in grass and shrub-dominated environments. In addition, the persistence of anomalous conditions following rainfall events is similar across the ecotone. Therefore, we conclude that plant type does not influence the nature of soil moisture-rainfall feedbacks in semiarid regions. In these environments, the soil moisture-rainfall interactions appear to be dominated by the magnitude and timing of rainfall events.

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