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Agricultural and Forest Meteorology 114 (2003) 127–139

AGRICULTURAL AND FOREST METEOROLOGY

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The understory and overstory partitioning of energy and water fluxes in an open canopy, semiarid woodland

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Received 1 April 2002; received in revised form 27 September 2002; accepted 27 September 2002

Abstract

Eddy flux studies have traditionally focused on total ecosystem exchanges of energy and water by making measurements in the well-mixed surface layer, but this approach does not provide information about the partitioning of the total ecosystem fluxes between overstory and understory sources and sinks. In more open canopy environments, information about partitioning of fluxes is often required in order to understand the relative importance and functioning of key ecosystem components and their response to climate forcing. In this paper, we present results from a series of experiments carried out in a riparian mesquite (*Prosopis velutina*) woodland. Three eddy covariance systems were deployed before, during, and after the onset of the summer rainy season to measure energy and water fluxes. One eddy covariance system was installed on a tower to measure whole ecosystem fluxes. The other two were installed at a height of 2 m, one in a relatively closed understory patch and the other in a more open understory patch. Our results indicate that the understory and overstory moisture sources were mostly decoupled. The trees apparently had access to deep moisture sources, and thus, their water use was relatively insensitive to local precipitation. In contrast, the contribution of the understory to the total ecosystem fluxes was highly variable due to the presence or absence of near-surface soil moisture.

Published by Elsevier Science B.V.

Keywords: Evapotranspiration; Eddy covariance; Mesquite; *Prosopis velutina*; Understory vegetation; Transpiration rate; Savannah

1. Introduction

Studies on mass and energy exchange between the land surface and atmosphere are now conducted on many different ecosystems across the globe (Baldocchi et al., 2001). These studies are carried out in order to understand the processes that regulate ecosystem functioning and quantify sources and sinks of atmospheric constituents, such as water and carbon dioxide. Typically, the mass and energy exchanges are measured from tall masts or towers located above the surface in order to determine the average exchanges from the whole ecosystem.

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0168-1923/02/$ – see front matter. Published by Elsevier Science B.V.
PII: S0168-1923(02)00197-1

The structure of forest and woodland ecosystems often includes an understory of grasses, forbs, shrubs or smaller woody plants. Turbulent exchange measurements made above forests only quantify fluxes from the whole ecosystem, and thus the relative contribution of the overstory and understory sources and sinks are not known. This may have important implications for data interpretation and modeling. The "big leaf" approach (i.e. modeling the land surface as a single source/sink surface) is commonly used when considering the forest as a whole. The degree to which this approach is adequate depends upon whether the forest overstory and understory processes are well coupled and whether the understory component is significant. The partitioning to the total ecosystem exchange into overstory and understory components can change due to factors, such as canopy architecture (Lamaud et al., 1996), water availability (Baldocchi and Vogel, 1997; Law et al., 2001), and vegetation functioning (Baldocchi and Vogel, 1996).

As turbulent exchange studies have become increasingly common, there are now a number of recent investigations that have examined understory exchanges in forest ecosystems (e.g., Baldocchi and Vogel, 1996; Blanken et al., 1997; Constantin et al., 1999; Baldocchi et al., 2000; Lamaud et al., 2001). The eddy covariance method is often used to measure the turbulent exchanges above the forest floor. Conditions found in the understory like low wind speed, large heterogeneity, and intermittent turbulence can invalidate the underlying assumptions of eddy covariance measurements. Thus, many investigators have sought to determine when such measurements are valid. Baldocchi et al. (2000) concluded that understory eddy covariance measurements exhibit much variability from one sampling period to the next due to the high spatial and temporal heterogeneity of solar forcing and turbulence, but they found good agreement between turbulent energy fluxes and available energy (i.e. closure) by averaging measurements over several hour runs. In a study involving a deployment of multiple eddy covariance instruments in the understory, Wilson and Myers (2000) also highlight the fact that 0.5 h turbulent fluxes are highly variable and should be used judicially. Their results indicated that sensor-to-sensor variability decreased as the fluxes were averaged, and they suggest that a 4–24 h period may be a reasonable averaging time to obtain representative understory fluxes. All of these studies promote energy balance closure as the best test for determining the validity of understory eddy flux measurements.

In this paper, we highlight the results of a series of experiments that examined the use of eddy covariance instruments located above the understory and above the overstory to determine the partitioning of energy and water vapor fluxes between the overstory and understory[1] sources. These experiments were carried out in a riparian mesquite (*Prosopis velutina*) woodland with a significant understory of perennial grasses and annual forbs. The measurements were carried out when near-surface soil water availability was significantly different in order to determine how the understory/overstory partitioning of total ecosystem water use changes seasonally.

This study is motivated by the desire to better quantify the groundwater use of riparian vegetation following Scott et al. (2000) and Goodrich et al. (2000). Along with much of the healthy, intact riparian ecosystem, nearly all of the growing human population in the Upper San Pedro Basin relies on groundwater as a water resource. This reliance has created concern that groundwater mining has or will lower the water table below the root zone of the riparian vegetation and threaten the integrity of federally-managed Riparian National Conservation Area. To properly address this concern, a better quantification of the basin groundwater budget is needed along with an improved understanding of riparian vegetation functioning. Because the mesquite trees are facultative phreatophytes and the water table is ∼10 m below the surface at this location, we examine the extent to which the trees and understory vegetation use different water sources (ground versus surface water), thus, distinguishing tree transpiration, if shown to be derived from groundwater, from total ecosystem evapotranspiration is an important step in refining the basin groundwater budget and in improving our understanding of this important riparian ecosystem.

[1] As eddy flux measurements made above the forest floor do not distinguish separate plant and soil sources/sinks, the term "understory" used in this paper includes both the soil and sub-tree canopy plant surfaces.

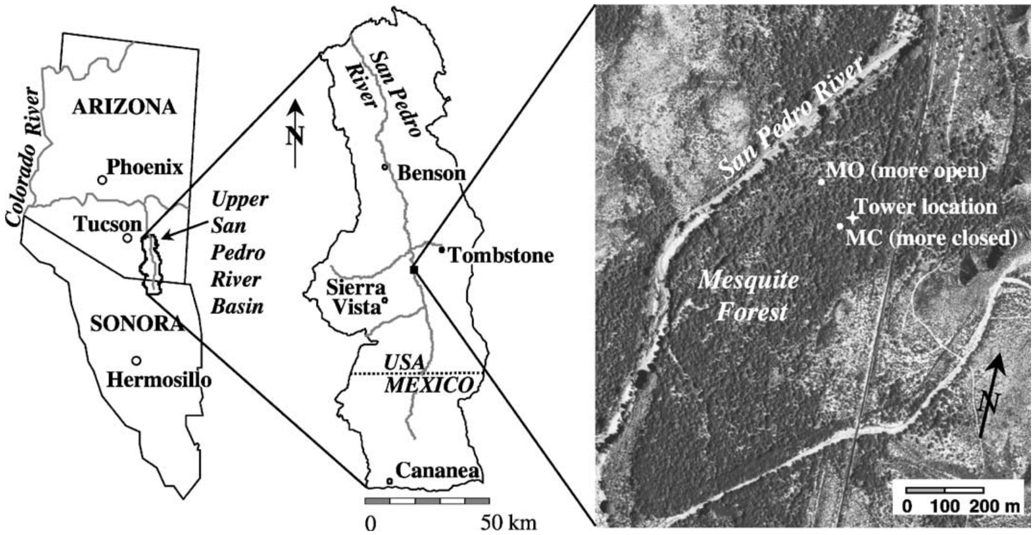

Fig. 1. Site location and layout of riparian mesquite study site.

2. Materials and methods

2.1. Site description

The site is located on an alluvial terrace near the San Pedro River in southeastern Arizona, USA (31°40′N, 111°11′W; 1190 m elevation). A location and site map are given in Fig. 1. The alluvial terrace is about 2 km north to south and 0.8 km wide east to west and is relatively flat (slope of 3–4%). The woodland lies between an entrenched perennial stream and the upper slopes of the surrounding valley. The average depth to groundwater is approximately 10 m. The overstory is dominated by the leguminous tree, velvet mesquite (*Prosopis velutina*), with an average height of about 7 m at the site. The average leaf area index is low (1.6), and the mesquites do not form a closed-canopy, nor are they of uniform height or age. Portions of the woodland are open and covered with abundant herbaceous vegetation. The understory is comprised mainly of a perennial bunchgrass (*Sporobolus wrightii*) and annual herbaceous dicots (*Lepidium thurberi*, *Chenopodium fremontii*, and *Viguiera dentata*). The average understory patch is comprised of about 95% plant and litter cover and 5% bare soil. The terrace soil is comprised of sandy loams interspersed with layers of gravels and layers of more clayey material. The site has a typical fetch of around 300–1000 m for the prevailing wind directions (southwest to west). The shortest fetch is limited to about 150 m southeast of the tower measurements.

The climate of the upper San Pedro valley is semiarid with temperatures ranging from a mean maximum temperature of 24.8 °C to a mean minimum temperature of 9.9 °C (1960–1990 averages recorded in Tombstone). The nighttime temperatures within the riparian corridor, where the site is located, are considerably colder (2–8 °C) than the rest of the valley due to cold air drainage. The precipitation distribution is bimodal, with about 60% of the 343 mm annual average rainfall occurring during the summer monsoon months of July through September and 23% occurring in the winter months of December through March.

2.2. Eddy flux measurements

A 14 m tower was erected in the forest to make long-term eddy covariance measurements above the canopy. This tower was positioned to maximize the fetch from the prevailing winds from the west and southwest (Fig. 1). From the top of the tower, near-continuous measurements of water vapor, sensible heat and carbon dioxide fluxes were made over the 2001 mesquite growing season. The canopy cover is about 70% within 150 m of the tower, but this density is not homogeneous and there are still considerable patches of understory. The percent cover of the green, understory vegetation in this denser portion of the forest ranged from approximately 5 to 15% perennial bunchgrass and 0 to 35% annual herbs from the pre-monsoon to the monsoon period. At a distance of 150–230 m and at a compass bearing of 215°–360°N from the tower, the understory patches are more open and frequent (40% overstory cover). The percent cover of the green, understory vegetation in these more open portions of the forest ranged from around 5 to 40% perennial bunchgrass and 0 to 20% annual herbs from the pre-monsoon to the monsoon period.

We deployed two eddy covariance systems to estimate the average understory flux sensed from the tall tower. One site, labeled MC, was located in a more closed patch near the tower, and the other, labeled MO, was positioned in a more open patch farther away (Fig. 1). Table 1 summarizes the eddy flux instrumentation and set-up used at the two understory sites and at the tower location. Understory eddy flux measurements were made during the periods 13–15 June, 27 July to 1 August, and 14–24 September to capture ecosystem function before, during and after the summer monsoon rains. The first two deployments, respectively, corresponded to likely periods of maximum and minimum stress (as quantified by vapor pressure deficit, air temperature and soil moisture availability).

The wind speed and concentration measurements were made at 10 Hz. The computation of 30 min covariances was calculated on-line by the dataloggers using Reynolds averaging. Due to equipment and power constraints, the raw data were not saved for the understory sites. Fluxes were later calculated off-line after performing coordinate rotations, accounting for density fluctuations following Webb et al. (1980), applying the "oxygen correction" for the Kypton hygrometer at the MO site (Tanner et al., 1993), and applying a correction for using the sonic temperature instead of air temperature in the sensible heat flux calculations following Liu et al. (2001). Prior to the experiments, both understory eddy covariance systems were installed side-by-side with the tower system for intercomparison. The computed sensible and latent heat fluxes agreed within root mean square errors of 30 W m^{-2} in both cases.

Because the fetch characteristics for our tower measurements not always ideal, it is important to examine the probable source area of the eddy flux measurements. During the periods of the experimental campaigns reported in this paper, winds were typically light (mean = 1.3 m s^{-1}, median = 1.0 m s^{-1}, at 14 m) and the wind direction was rarely from the southeast, where the fetch is limited to about 150 m. To get a sense if the eddy covariance measurements were representative of the ecosystem under study, the Flux Source Area Model of Schmid (1994, 1997) was used to map out the 50% source area. We acknowledge the limitations of this approach in that the model assumes the surface is homogeneous and that the canopy is closed. Clearly, these assumptions are not well met in our situation, but this quantitative tool is nonetheless helpful to estimate the representativeness of our tower measurements. We performed an analysis similar to that of Schmid (1997) where we mapped out the 50% source area boundaries for all the daytime tower fluxes during each of the campaigns. Ninety percent of the 50% source area isopleths lay within about 200 m of the tower. A diffusive scalar point source located on or outside of the 50% boundary would have to be 5–10 times stronger than a point source located at the maximum source weight, which is located well within the 50% source

Table 1
Summary of eddy covariance instrumentation and set-up at each of three measurement sites

	Tower	More open (MO)	More closed (MC)
Sonic anemometer	CSAT3[a]	CSAT3[a]	CSAT3[a]
Infrared gas analyzer (IRGA)/hygrometer	Li7500[b] IRGA	KH-20[a] hygrometer	Li7500[b] IRGA
Datalogger	CR5000[a]	23X[a]	23X[a]
Mounting height/sonic to IRGA separation distance	14 m/0.2 m	2 m/0.2 m	2 m/0.2 m

The use of these and other commercial names is not intended as an endorsement of the product.
[a] Campbell Scientific, Logan, UT, USA.
[b] LI-COR, Lincoln, NE, USA.

area boundary, in order to produce a similar response in the tower-located sensor (Schmid, 1997).

Below-canopy flux footprints are expected to be much less extensive compared to those above the canopy because the wind is less in these locations. Using another source area model, Baldocchi et al. (2000) found that the "flux footprint" ranged between 1 and 50 m upwind of an understory flux measurement made at 2.5 m height below a fairly open, old growth ponderosa pine stand. Similarly, Law et al. (2001), using the same footprint model, determined that 90% of the measured flux originated from within 32 m of a 3.6 m high sensor mounted under a young ponderosa pine canopy. The relatively small source area for sub-canopy measurements necessarily means there will be considerable variability in the measured fluxes of sensible heat and water vapor because these will be derived from different areas of plants and bare soil subject to variable solar forcing.

Many of the results presented in this paper are averaged over the diurnal cycle. On days with incomplete data, simple linear interpolation was used to fill small data gaps prior to calculating the diurnal average.

2.3. Additional instrumentation

Net radiation was measured differently for all three locations. At the tower site, a Kipp and Zonen (CNR1, Delft, The Netherlands) four-component radiometer mounted at 8.8 m height measured net radiation above the canopy. At the MO site, a single net radiometer (Q7.1, Radiation and Energy Balance, Seattle, WA) at 2 m height was used because the canopy was very open. At the MC site, understory net radiation was measured as being the average measurement from four distributed net radiometers (Q7.1) mounted at a height of 1 m. All of the REBS net radiometers were calibrated against the four-component radiometer prior to the study. The calibrated net radiometers agreed within an average root mean square error of 13.7 W m^{-2}. The CNR1 was recently calibrated at the manufacturer, and the reported accuracy of the instrument was ±10%.

Ground heat flux was measured by installing soil heat flux plates (REBS Inc., Seattle, WA) at 0.05 m below ground level. The soil temperature above the heat flux plates was found by averaging soil thermocouple measurements made at 0.02 and 0.04 m. The soil heat flux at the surface was then calculated by adding the measured heat flux at 0.05 m to the change in energy stored in the layer above the heat flux plates (0–0.05 m), this being proportional to the rate of change of soil temperature measured by the soil thermocouples. The specific heat of the 0.05 m thick soil layer was estimated using a thermal properties sensor (TP01, Hukseflux, Delft, The Netherlands). At the tower and MC sites, the average ground heat flux was calculated from ground heat flux measurements made at eight locations near the tower. For the MO site, two ground heat flux measurements (under grass and bare soil) located in the canopy opening were used to give the average ground heat flux.

We also monitored water content in the vadose zone and the depth to groundwater. Soil thermocouples and water content reflectometers (CS615, Campbell Scientific Inc., Logan, Utah) were installed in a vertical profile at 0.05, 0.1, 0.20, 0.30, 0.50, 0.70 and 1.0 m depth to measure the soil moisture under the site. A network of piezometers with water level transducers (MiniTROLL in situ Inc., Laramie, WY) measured the fluctuations in the water table. Finally, a tipping bucket gage measured precipitation from the top of the tower.

3. Results and discussion

To provide a context for the studies reported herein, Fig. 2 shows the observed precipitation and soil moisture profile during the mesquite growing season in 2001. The timing and duration of the three periods when overstory/understory comparisons were made are also indicated. During the initial, pre-monsoon campaign (13–15 June) the mesquite trees were fully leafed, while the understory grasses appeared to not be very active (i.e. there were only a few green shoots observed) and annual species had not yet emerged.

The timing of the pre-monsoon and monsoon (27 July to 1 August) campaigns coincided extremely well with periods of maximum and minimum surface soil moisture: 87 mm of rain had fallen and the average 0.05 m volumetric soil moisture went from 0.03 to 0.10 cm^3 cm^{-3}. Consequently, the understory was well developed and apparently active (i.e. both the grasses were greener and there was abundant growth of annual herbaceous species) in the second campaign. The post-monsoon campaign of 14–24 September occurred after most of the monsoon activity had

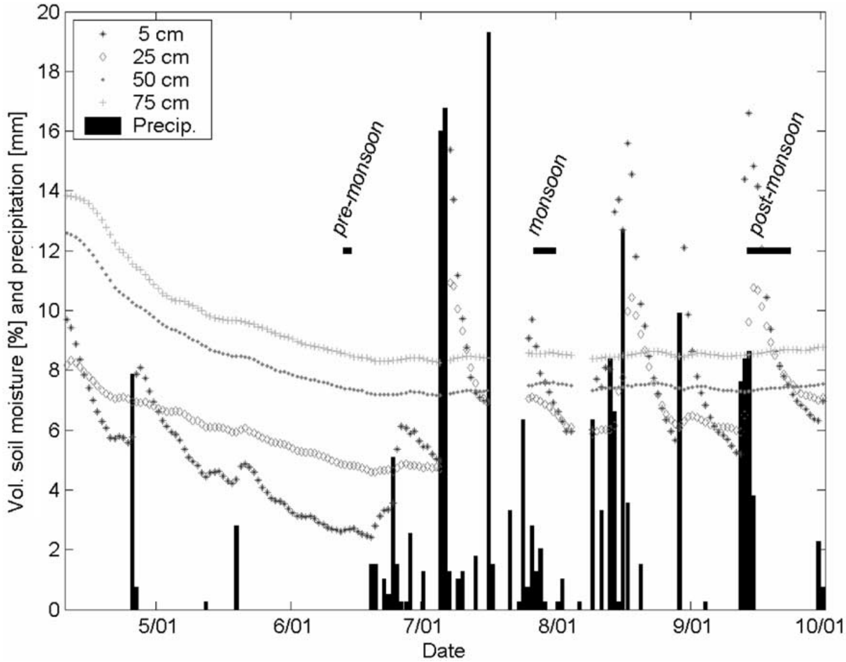

Fig. 2. 2001 growing season precipitation (mm per day) and volumetric soil moisture (%) at 0.05, 0.25, 0.50, and 0.75 m depth.

ceased. However, precipitation was high (28 mm over a 4-day-period) at the start of this final campaign, and this provided an opportunity to monitor the effects of soil moisture dry-down on the partitioning of overstory/understory fluxes. Although, conditions at the start of the final campaign were as wet as during the monsoon period, the understory vegetation had already started to senesce. A few of the mesquite trees had also begun to drop some of their leaves.

3.1. Energy balance closure

An essential test to investigate the validity and applicability of eddy covariance measurements is to determine how well the available energy (i.e. net radiation, R_n, minus ground heat flux, G) is balanced by the sum of the turbulent fluxes (i.e. the sum of the latent, λE, and sensible, H, heat fluxes). How well this simplified energy balance ($R_n - G = \lambda E + H$) is closed depends both on the validity of the eddy covariance measurements and the ability to adequately quantify the available energy of the flux source area. Unfortunately, the area sampled by the turbulent fluxes and that over which available energy (indeed, both the net radiation and the ground heat flux) is measured often differ. This is arguably less of a problem for above-canopy measurements than below-canopy measurements because, in the latter case, light conditions are much more heterogeneous, and the smaller footprints of the turbulent fluxes are more likely to be dominated by individual sources.

Fig. 3 shows the sum of the turbulent fluxes relative to the available energy for all three sites for all measurement periods. Each symbol corresponds to one 30 min measurement. The one-to-one line is also given, and the coefficient of determination, R^2, and the slope of the best-fit line through the zero intercept are also given. Recall that for the MO site, R_n and G were measured locally with just one radiometer and two heat flux plates (Fig. 3a). The acceptable closure (0.85) at this site indicates that the source area was quite localized, with fluxes originating mainly from the open patch. For the tower site (Fig. 3b), closure (0.81) during these experimental periods is comparable to that seen throughout the entire growing season (not shown). In these plots, the rate of change of stor-

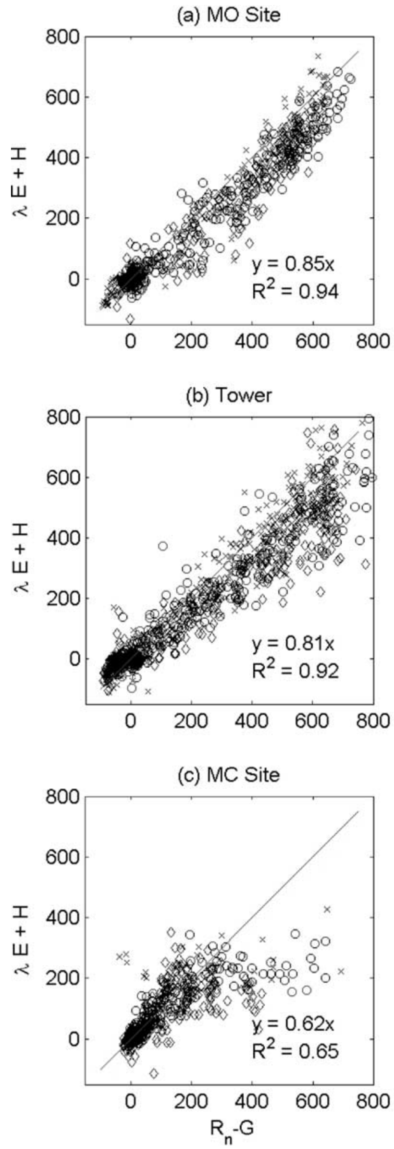

Fig. 3. Energy balance closure for the (a) MO, (b) tower, and (c) MC sites during the pre-monsoon (×), monsoon (◯), and post-monsoon (◇) campaigns. Units are in $\mathrm{W\,m^{-2}}$. Also, the best-fit line through the origin and coefficient of determination, R^2, are given.

age of sensible heat and latent heat in the biomass and air column below the net radiation measurement are not included. The storage of energy in the air column was insignificant, but we estimate that the energy storage in the biomass below the tower was about 5–10% of the quantity, $R_n - G$, based on daily closure analysis. Remarkably, the high value of R^2 value for the MO site indicates that the variability between runs is similar to the above-canopy measurements. This is likely due to the large canopy opening at this site, and ability of light and wind (to a lesser extent) to penetrate more effectively into this gap. Fig. 4 presents an example of how wind speed and net radiation vary diurnally between the three sites. The large values for the net radiation at the tower site is mainly due to the woodland's small, short-wave albedo of ∼0.08.

For the MC site (Fig. 3c), R_n is the average of four (only three during the pre-monsoon campaign) separate radiometers distributed throughout the understory, and G the average of eight heat flux plates. These results suggest that understory net radiation is inadequately sampled by just four radiometers under this very heterogeneous canopy. There is reasonable closure for available energies below $\sim 300\,\mathrm{W\,m^{-2}}$, but poor closure above this value. The difference when available energy is higher is likely due to unintentional bias in the placement of radiometers, these being positioned more towards canopy gaps rather than towards areas with dense tree canopy coverage. It was, for instance, observed that three of the four radiometers were positioned, such that they were simultaneously exposed to direct sunlight around mid-day. This is a clear case of mismatch between the area sampled by the radiometers and that sampled by the turbulent fluxes, which would likely be a mixture of both sunny and shady patches. We assume that the poor overall agreement between the eddy covariance measurements and the estimated available energy at this site was due mainly to source area mismatch, especially around mid-day, rather than a bad eddy covariance measurement per se.

3.2. Understory/overstory partitioning of energy and water fluxes

Flux partitioning depends on both the available energy near the surface, which is determined by stand structure and density, and available water, which is determined by antecedent moisture and plant water source. Fig. 5 presents the daily average net radiation for all three sites for the three campaigns. There is a dramatic difference between these two understory patch types: the MC site received about 50% less net radiation than the MO site. Most likely, the difference

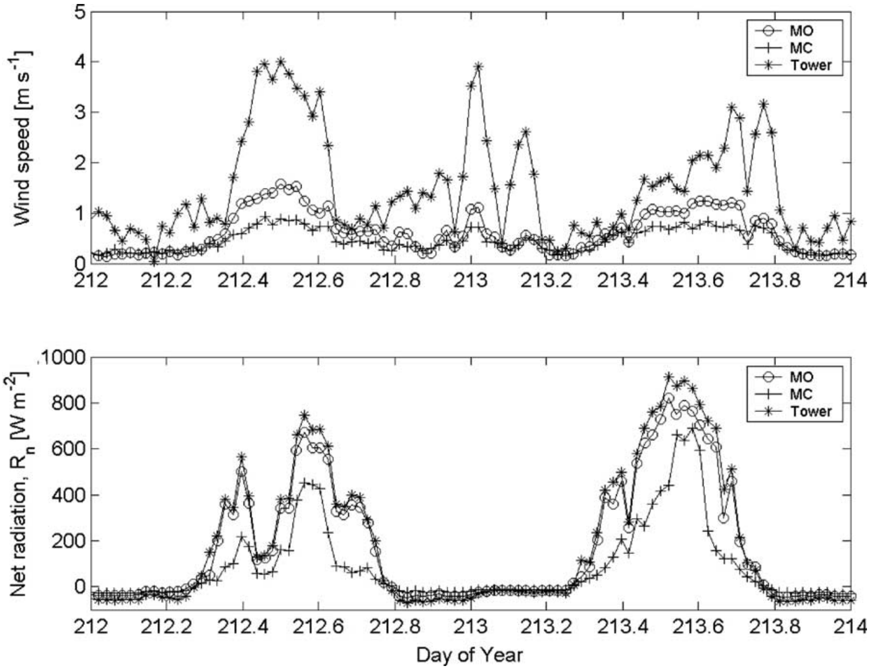

Fig. 4. Example of the diurnal, intersite variation of the wind speed ($m\,s^{-1}$) at sensor height and the net radiation ($W\,m^{-2}$) for 31 July and 1 August 2001.

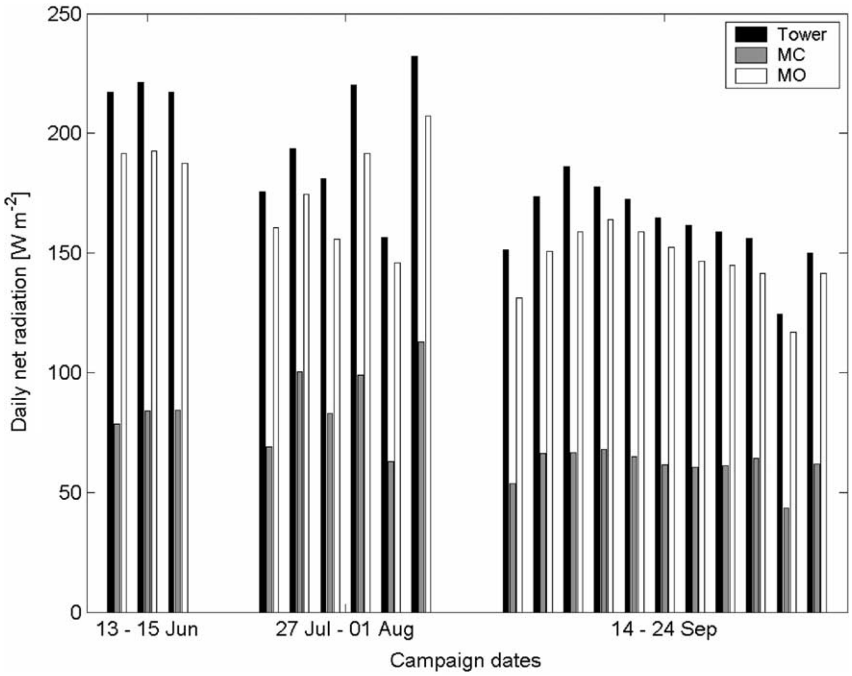

Fig. 5. Daily average net radiation ($W\,m^{-2}$) for all three sites.

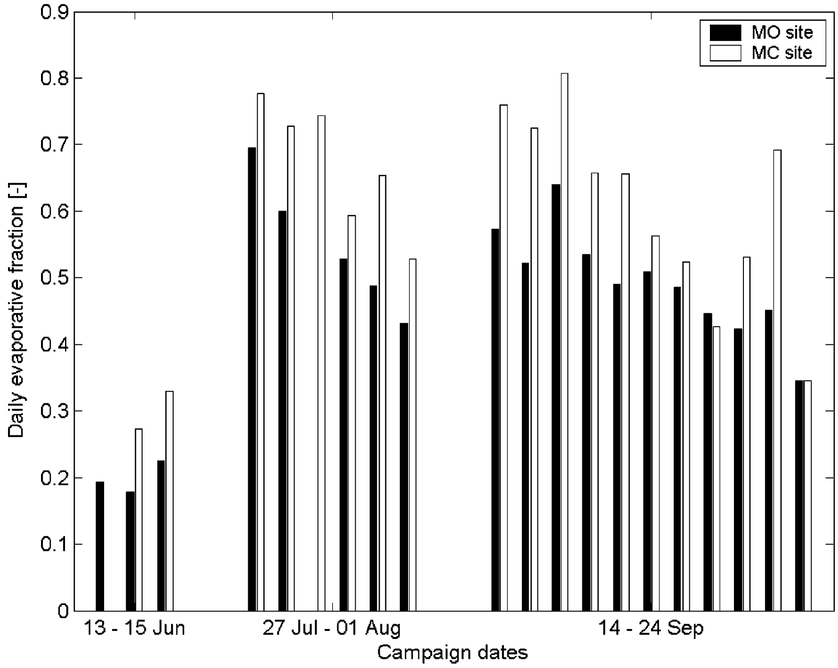

Fig. 6. Daily average evaporative fraction for both understory sites.

is even greater due to our supposition that measured net radiation for the MC site is biased high. Typical daytime soil heat fluxes ranged around 10–20% of net radiation at the MO site and around 20–50% of net radiation at the MC site. To illustrate how this radiant energy is partitioned into latent and sensible heat fluxes, Fig. 6 shows the daily average evaporative fraction ($\lambda E/\lambda E + H$) for the two understory sites. There is an encouraging similarity in the relative behavior at the two sites, although the MC site consistently had a higher evaporative fraction except toward the very end of the last campaign.

As expected, the evaporative fraction (Fig. 6) during the pre-monsoon campaign was much lower than during the subsequent campaigns because understory root-zone soil moisture was scarce (Fig. 2). The decreasing evaporative fraction during the last two campaigns is probably due to a fall in bare soil evaporation. In the absence of rain, the soil dries quickly and its contribution to total understory evapotranspiration falls rapidly. During the final (September) campaign, the evaporative fraction falls to near pre-monsoon levels, although the near-surface soil was considerably wetter. We suspect that this was because the understory vegetation, especially the annual species, were already showing signs of senescence; the onset of senescence being likely caused by an extended dry period (18 August to 12 September) when there was only 10 mm of rain (on 29 August). There was a larger amount of annual species around the MC site while perennial bunchgrass was more dominant at the MO site.

Finally, Fig. 7 shows the daily average values of ecosystem water use (measured on the tower) and how much of this total water loss is derived from the understory. In this figure, the average understory evaporation is computed by, $0.7\overline{E_{\mathrm{MC}}}+0.3\overline{E_{\mathrm{MO}}}$, where $\overline{E_{\mathrm{MC}}}$ and $\overline{E_{\mathrm{MO}}}$ are the average daily evaporation from the more closed and more open sites, respectively. This weighted average reflects the average canopy cover (∼70%) of the mesquite overstory and that the source area of the tower measurement is likely to have a similar weighting of more closed and more open patches. The Penman potential evaporation (PET, Shuttleworth, 1993), a measure of the atmospheric demand, and the product of the daily water table fluctuation measured in a local piezometer and a specific yield ($\Delta WT^{*}S$) are also showing in Fig. 7. Multiplication of the water table fluctuation by a specific yield is required to get

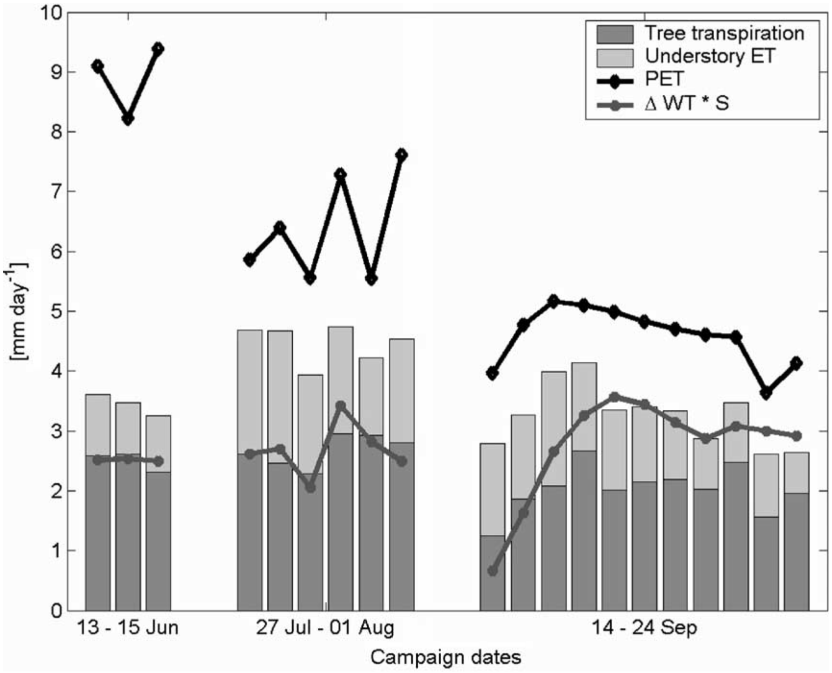

Fig. 7. Total daily evaporation from the mesquite ecosystem (total bar height) and its partitioning into overstory/understory sources. Additionally, the Penman potential evaporation, a measure of the atmospheric demand, and the product of the maximum daily water table fluctuation (as measured in a local piezometer) and an estimated specific yield are shown. All units in mm per day.

an equivalent depth of water removed from storage (volume per unit area) since only a portion of the soil matrix can store water. The specific yield (0.067) was estimated by taking the average pre-monsoon and monsoon daily total tree transpiration and dividing by the average daily water table change.

Not withstanding the changes in near-surface soil moisture, overstory water use (i.e. mainly tree transpiration) was nearly constant during the pre-monsoon to monsoon periods (Fig. 7); the coefficient of variation for the pre-monsoon and monsoon estimates of overstory water use is 9.3%. Thus, the difference in total ecosystem water use is principally due to changes in the understory evapotranspiration. This argues for the case of a bifurcated water source shown schematically in Fig. 8 and similar to the model proposed by Walker and Noy-Meir (1982). Our two-source system differs from their model because the deeper, tree water source is likely derived from the water table as opposed to infiltration percolated past the understory plant root zone. Cut-banks along the river edge reveal many mesquite roots reaching down the ∼10 m depth that is

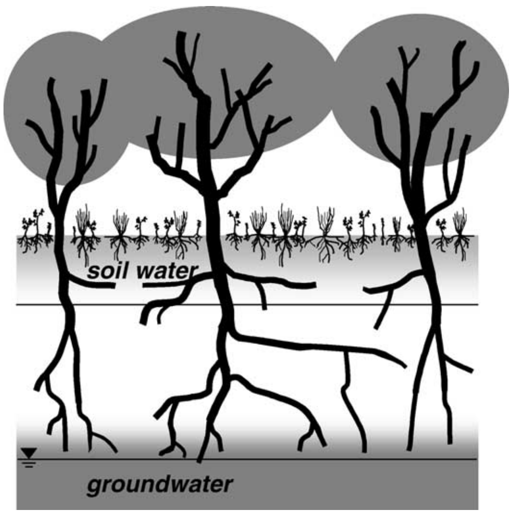

Fig. 8. Schematic of hypothesized two-source water ecosystem. Taproots of trees can access groundwater source (∼10 m depth) whereas understory grasses/annuals are dependent on local precipitation.

required to access groundwater. Additionally, our data reveals that the trees certainly had access to a source of deeper vadose zone water during the pre-monsoon campaigns and tree transpiration did not change significantly when near-surface soil moisture increased. Although it is possible that the trees changed from a deep to a shallow moisture source during the monsoon, this is unlikely because it would require a significant investment of resources to entirely alter their hydraulic architecture. Furthermore, we find a strong correlation between daily tree water use and daily water table fluctuation. This agreement did not change from the pre-monsoon to the monsoon campaigns.

As the season progressed, the relationship between potential evaporation and ecosystem evaporation changed, indicating a transition from surface-controlled (water or plant limited) towards atmospheric demand-controlled evaporation (Fig. 7). In the pre-monsoon campaign, large vapor pressure deficits and cloud-free days resulted in a much greater atmospheric demand (as quantified by the potential evaporation) that the surface could not supply. Consequently, the overstory and understory evaporation rates changed little from day to day. There is some evidence of a heightened variability in the daily evaporation rates, especially for the understory, that increased during the monsoon as surface water availability increased and the atmosphere's ability to transport water vapor away from the surface decreased. This variability becomes more obvious in the post-monsoon campaign. In September, the weather was cloudy and rainy for the first few days of the campaign, followed by mostly fair skies for the remainder. There was a gradual dry-down of the understory, while the overstory had evaporation rates only slightly less than in June and July. The constant of proportionality between the water table fluctuations and overstory evaporation also changed during the post-monsoon campaign, perhaps due to the lower water levels in the piezometer. At a lower water table elevation, a portion of the aquifer with different hydraulic properties might have been influencing water levels. Unfortunately, we did not have a way to verify this suggestion.

There is evidence in our results that the mesquite trees can impose strict physiological limitations on water transport. During this study, the maximum daily tree transpiration was always limited to less than 3 mm per day, even during periods of high atmospheric demand. Average daytime canopy resistance, computed by inverting the Penman–Monteith equation (Monteith, 1965), overstory latent heat fluxes and available energy, changed from 350 $\mathrm{s\,m^{-1}}$ during the pre-monsoon to 150 $\mathrm{s\,m^{-1}}$ during the monsoon campaign. Furthermore, average canopy resistances rose from ∼150 to ∼300 $\mathrm{s\,m^{-1}}$ during the dry-down in the post-monsoon campaign as maximum vapor pressure deficits increased from 1.3 to 4.3 kPa.

Finally, it is important to recognize, to some extent, that our results depend on the formula we used to calculate average understory evaporation. During most of the time during the measurement campaigns, the majority of the water vapor flux measured on the tower originated within about 200 m of the tower, but some portion of the measured flux will always originate from sources beyond this distance. For any given 30-min sampling period, the weighting used to compute the average value from the two understory measurements was 70% MC and 30% MO, but, in reality, this weighting should change from one time step to the next (e.g. as the wind speed changes). The results presented above rely on temporal averaging (e.g. taking daily averages) to reduce the variability in the 30 min measurements so that measured fluxes at all sites are more representative of average surface characteristics. In practice, it would be difficult, and probably impossible, to use variable weighting to calculate average understory flux for every 30 min interval because of the inaccuracies in source areas models when applied to field conditions, and because of the questionable representativeness of the 30 min understory flux measurements. Fortunately, our results are insensitive to the understory averaging weights used. Changing the understory averaging formula from $(0.7\overline{E_{\mathrm{MC}}} + 0.3\overline{E_{\mathrm{MO}}})$ to $(0.85\overline{E_{\mathrm{MC}}} + 0.15\overline{E_{\mathrm{MO}}})$, for example, increases the average "tree transpiration" (Fig. 7) by just 0.05, 0.13 and 0.11 mm per day during the June, July and September campaigns, respectively. These changes are small (<5%) and certainly within the error of the flux measurements.

4. Summary

In this study, eddy covariance instruments were used above and below the canopy of riparian woodland to document the proportion of energy and water fluxes that originated from the canopy and the understory, and how this varied seasonally. Our results suggest that using eddy covariance measurements was appropriate for this purpose because acceptable (although not perfect) energy closure was demonstrated. However, poor energy closure in the case of understory fluxes beneath a more closed canopy suggests the need for more thorough sampling of the highly heterogeneous net radiation to ensure closure in this case. The heterogeneity of the canopy in our study resulted in very different forcing at the two understory sites. The available energy and turbulent mixing at the more open understory site was much higher. Nevertheless, we found relatively good agreement between variations in the daily average understory evaporative fraction between the two understory sites, indicating that at both locations evaporation was similarly influenced by vegetation and water status. When daily average understory water flux was separately identified within the total ecosystem water use, the overstory water use was found to be relatively constant despite changes in surface water availability. Additionally, overstory water use was well correlated with water level fluctuations. On the basis of this evidence, we conclude that the trees acquired most of their water from a deep, groundwater source whereas understory vegetation relied mainly on recent precipitation.

These results have important implications in the context of quantifying the groundwater use of riparian mesquite woodlands. Tower measurements alone would have overestimated the groundwater use for this ecosystem because the contribution of the understory apparently relies only on surface water. Our results suggest that trees in this ecosystem acquire the majority of their water from groundwater. Therefore, it is plausible to suggest that a simple subtraction of the local precipitation (less tree interception) from the measured total ecosystem evapotranspiration will give a reasonable estimate of groundwater use by the mesquites when averaged over several weeks or months. Riparian mesquite woodlands do, indeed, have a significant impact on the regional groundwater water balance because they are the dominant riparian ecosystem along the San Pedro River and they appear to obtain most of their water from groundwater. Conversely, the health of mesquite woodlands is likely to be impacted by groundwater overdraft in the basin.

Acknowledgements

This work is supported in part by SAHRA (Sustainability of Semi-arid Hydrology and Riparian Areas) under the STC Program of the National Science Foundation, Agreement No. EAR-9876800. Additional financial support was provided to USDA-ARS from the Upper San Pedro Partnership. We would also like to thank Enrico Yepez-Gonzalez for the vegetation data, along with the Fort Huachuca Meteorological Support team, US Bureau of Land Management, and especially all the rest of the staff from the USDA-ARS located in Tucson and Tombstone, Arizona for their invaluable support of this work.

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