



# Interannual and seasonal variation in fluxes of water and carbon dioxide from a riparian woodland ecosystem

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Received 7 April 2003; received in revised form 3 September 2003; accepted 3 September 2003

## Abstract

Fluxes of water, energy and carbon dioxide (CO<sub>2</sub>) were measured using the eddy covariance technique over a mesquite (*Prosopis velutina*) woodland along the San Pedro River in southeastern Arizona for the entire growing seasons of 2001 and 2002, between the last freeze event of spring and the first of fall. Although the general pattern of ecosystem response to climate forcing was similar in both years, latent heat and CO<sub>2</sub> fluxes showed significant variations between and within the growing seasons. The main differences between the two years were a consequence of an extended drought that lasted from October 2001 to July 2002. Most of the within season variability was attributable to the timing and magnitude of mid-summer precipitation associated with the North American Monsoon. Following new tree leaf production and prior to the monsoon onset, there was little precipitation; daytime air temperatures were high and relative humidity low. Evapotranspiration and water level data indicated that the mesquite trees always had ready access to groundwater, though they were likely supplementing this with vadose zone soil water when abundant. Nonetheless, decreases in afternoon transpiration and CO<sub>2</sub> uptake suggest stomatal regulation of leaf gas exchange, possibly in response to the high vapor pressure deficit. Because near-surface soil moisture was limited prior to the summer rains, ecosystem respiration was low and there was little evapotranspiration from understory plants and soil. With the arrival of the monsoon rains, understory vegetation activity and, consequently, total ecosystem evapotranspiration increased. Total ecosystem photosynthesis also increased, but the net uptake of carbon decreased, due to enhanced respiration from the abundant carbon sources, stimulated by the precipitation and warm temperatures. The nighttime measurements of CO<sub>2</sub> fluxes, although of questionable accuracy, imply the ecosystem was a net sink of CO<sub>2</sub> for most of the two growing seasons.

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**Keywords:** Evapotranspiration; Carbon dioxide exchange; Eddy covariance; Energy balance; Riparian vegetation; Mesquite; *Prosopis velutina*

## 1. Introduction

Riparian corridors are hot spots of biological activity and provide valuable habitat in semiarid regions such as the southwestern United States. With potential access to surface water and shallow groundwater,

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riparian ecosystems maintain high levels of biodiversity and production compared to the surrounding desert (Brown, 1982). At the same time, rural and urban development often impact the vitality of riparian areas by changing land use and by diverting water and lowering the water table (Jackson et al., 2001). Understanding how climatological factors that drive eco-hydrological function interact with changing societal demands and climate variability is important for improving our management of such vital ecosystems.

The San Pedro River in southeastern Arizona is a good example of a riparian area facing pressure from urbanization. Located within the basin and range physiographic province, the San Pedro River flows intermittently over 250 km from its headwaters in Sonora, Mexico to its confluence with the Gila River in south-central Arizona. The basin is underlain by aquifers that are recharged primarily at the mountain-front pediments. The aquifers support baseflow in portions of the river and provide water for communities in the basin. The largest community is Sierra Vista, with a population of approximately 40,000 that is growing 2.2% per year (City of Sierra Vista, 2002). Population growth in the Upper San Pedro valley and the resulting increase in groundwater pumping have created concern that the water table may fall below the rooting zone of the riparian vegetation. Because surface and ground water are linked, the health of the riparian ecosystem therefore depends on careful management of water resources within the basin (Commission for Environmental Cooperation, 1999).

Groundwater modeling studies indicate that water use by riparian vegetation is an important component of the water balance in the basin (e.g. Corell et al., 1996). Recently, knowledge of the functioning of semiarid riparian ecosystems and their possible response to changes in climate or water availability has improved (Stromberg et al., 1996; Unland et al., 1998; Goodrich et al., 2000; Scott et al., 2000; Schaeffer et al., 2000; Snyder and Williams, 2000; Cleverly et al., 2002). Along the San Pedro, ecosystems that contain mesquite (*Prosopis velutina*)—a facultative phreatophytic tree—comprise the largest area. Goodrich et al. (2000) indicated that groundwater use by mesquite was likely the largest but most uncertain component in the total riparian consumptive groundwater budget in the Upper San Pedro Basin. Determining the amount of groundwater withdrawal

by mesquite and how this changes through the year is therefore important for improved water management in the basin. Previous studies of riparian mesquite (Unland et al., 1998; Scott et al., 2000) primarily focused on the water use of the trees, with little or no attention given to other aspects of ecosystem functioning.

This study documents the magnitude and variability of water vapor and carbon dioxide (CO<sub>2</sub>) fluxes from a mature, dense woodland of mesquite along the San Pedro River during the 2001 and 2002 growing seasons in order to:

1. Quantify the growing season energy balance and evapotranspiration for model development.
2. Determine characteristic diurnal cycles of latent heat flux and net ecosystem exchange of CO<sub>2</sub> (NEE) to expand our understanding of these inter-related processes.
3. Examine how evapotranspiration and NEE are related and how these are linked to the overstory and understory primarily having different water sources in order to constrain our understanding of ecological functioning.
4. Determine how the above vary across and between 2001 and 2002 growing seasons to understand the role of climate variability in a semiarid region with a monsoon climate.

The mesquite growing season in southern Arizona typically experiences dramatic changes in forcing due to the mid-summer arrival of the North American Monsoon. The first part of the season is typically very warm and very dry; the middle part is wet and more humid; and the end is dry and less humid. Consequently, we expected that water vapor and CO<sub>2</sub> fluxes will exhibit a large degree of variability similar to other sites with dramatic shifts in forcing (Verhoef et al., 1996; Eamus et al., 2001; Vourlitis et al., 2001). The values of evapotranspiration measured in this study probably provide an upper estimate of mesquite water use in this basin because the study site has a relatively high density of large trees relative to mesquite stands further from the river which are more shrubby, less dense, and likely non-phreatophytic (Stromberg et al., 1993). Similarly, the CO<sub>2</sub> fluxes measured for the mesquite ecosystem at the study site are likely to be large relative to ecosystem fluxes outside the riparian corridor.

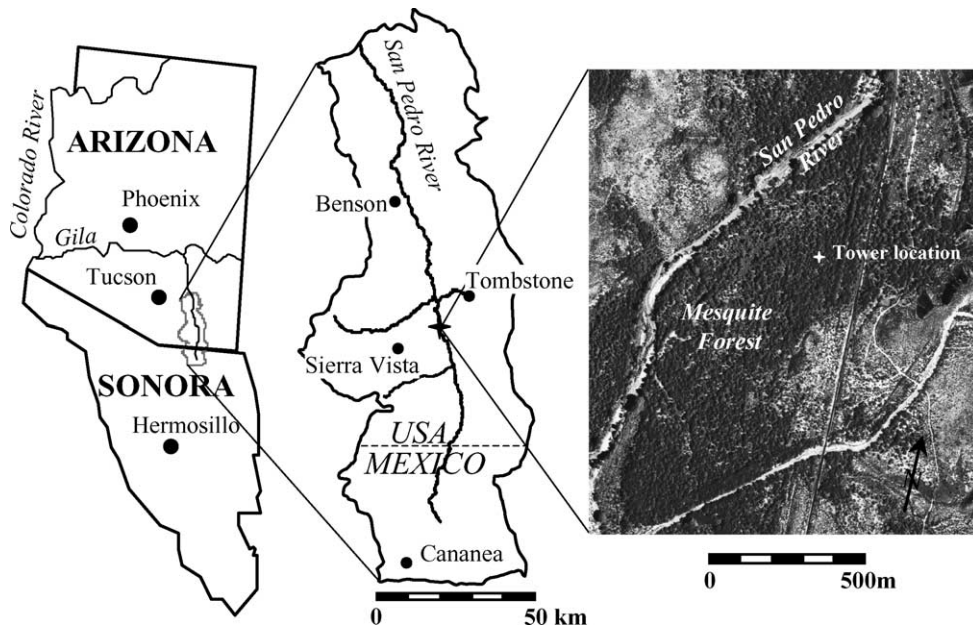


Fig. 1. Location of study site within the Upper San Pedro Basin. Lighter-colored terrain outside the mesquite woodland is typically Chihuahuan desert scrub. Across the lower right portion of the photograph is an ephemeral wash flowing into the San Pedro River.

## 2. Site description

The mesquite woodland study site ( $31^{\circ}39.8'N$ ,  $110^{\circ}10.7'W$ ) is located on the east side of the San Pedro River at an elevation of 1200 m, approximately 16 km northeast of Sierra Vista, Arizona (Fig. 1). The climate of the Upper San Pedro valley is semiarid, with summer mean air temperatures around  $26^{\circ}C$  (mean maximum temperatures around  $34^{\circ}C$ ) and mean annual precipitation measured between 1971 and 2000 in Tombstone, Arizona, which is about 13 km northeast of the site, is 358 mm (Western Regional Climate Center, <http://www.wrcc.dri.edu>). Approximately 60% of the annual precipitation falls during the summer monsoon season that typically occurs between July and September. A second, more erratic rainy season occurs between December and March, but late spring and early autumn are typically very dry and hot. Summer rains are the result of local thunderstorms, causing high variability in the location and intensity of rainfall. Winter precipitation is mainly from frontal systems, resulting in less intense and more uniform rainfall.

The entrenched river channel supports a narrow, linear forest gallery of cottonwood (*Populus fremontii*) and willow (*Salix gooddingii*). On the alluvial terrace above the entrenchment, there is a woodland ecosystem which is dominated by the leguminous tree, velvet mesquite (*P. velutina*), with an understory primarily of sacaton grass (*Sporobolus wrightii*) with some greythorn shrubs (*Zizyphus obtusifolia*) and various annual herbaceous species. The average canopy cover is  $\sim 70\%$  within 150 m of the tower, but this density is not homogeneous and there are sizeable gaps in the canopy. The measured leaf area index (LAI) (LI-2000, LI-COR, Inc., Lincoln, NE) ranges from an average ( $n = 40$ ) of  $\sim 1.0$  prior to leaf-out to  $\sim 1.6$  during most of the growing season. The mean canopy height is approximately 7 m and the maximum canopy height  $\sim 10$  m. The woodland is about 600 m wide on a terrace that extends at least 1500 m along the river (Fig. 1). Beyond the forest and above the riparian valley, the vegetation reverts to Chihuahuan desert scrub. The deepest rooting depths of the understory plants have not been observed to be greater than 2–3 m, implying that they do not have access to the groundwater

at a depth of  $\sim 10$  m. Rooting patterns of non-riparian mesquite are quite varied and extensive (Heitschmidt et al., 1988) and have been described as “ubiquitous” (Gile et al., 1997). From cut-banks along the river near our site, we have observed mesquite roots extending both laterally near the surface and vertically all the way down to the water table. On the terrace, soils are sandy loams interspersed with layers of gravel and clayey material. Under the trees, the soil is typically covered with a thin (2–3 cm) layer of organic matter composed mainly of mesquite leaves, fruit, and woody material.

### 3. Methods

#### 3.1. Instrumentation and measurements

Latent heat,  $\text{CO}_2$  and sensible heat fluxes were measured using the eddy covariance technique from 1 April to 28 November (day of year (DOY) 1991: 332) in 2001 and 2002. Basic meteorological, soil moisture, and groundwater height data were also collected throughout most of both years. A three-dimensional sonic anemometer (Model CSAT3, Campbell Scientific, Inc., Logan UT) and an open path infrared gas analyzer (IRGA; Model LI-7500, LI-COR, Inc., Lincoln, NE) mounted at a height of 14 m at the top of a scaffolding tower measured the three components of the wind velocity vector, sonic temperature, and the densities of water vapor and  $\text{CO}_2$ . These were sampled at 10 Hz by a datalogger (CR5000, Campbell Scientific, Logan, UT) which also calculated their 30 min covariances using block Reynolds averaging. Surface fluxes were later calculated off-line, after performing a two-dimensional coordinate rotation and accounting for density fluctuations (Webb et al., 1980). The sonic temperature was used to calculate sensible heat flux using the method suggested by Paw U et al. (2000) which accounts for a missing energy balance term associated with the expansion of air during evaporation under constant pressure. Fluxes measured when the wind was within  $20^\circ$  of north (approximately 6.3% of the data) were ignored due to possible interference from the anemometer support and the IRGA mounted behind the anemometer.

Measurements were made with a wind vane/anemometer (R.M. Young Co., Traverse City, MI) and

a temperature/relative humidity probe (HMP35D, Vaisala, Helsinki, Finland) at a height of 13.5 m, and above-canopy net radiation was measured at a height of 9 m using a four-component radiometer (Model CNR 1, Kipp & Zonen, Delft, The Netherlands) attached to a horizontal boom extending 4 m from the tower. Ground heat flux was measured with eight soil heat flux plates (REBS, Inc., Seattle, WA) installed 0.05 m below ground level. Measurements of the rate of change of soil temperature above the heat flux plates (at 0.02 and 0.04 m) allowed calculation of the soil heat flux at the surface using estimates of the specific heat of the 0.05 m thick soil layer obtained with a thermal properties sensor (TP01, Hukseflux, Delft, The Netherlands).

Soil moisture was measured with 12 water content reflectometers (Model CS615, Campbell Scientific, Inc., Logan, UT) installed in profiles at depths of 0.05, 0.10, 0.20, 0.30, 0.50, 0.70 and 1.0 m. Two probes were installed at each of the five upper depths, and the reported data for these depths represent an average of the two. A network of piezometers was installed to measure fluctuations in the water table. Measurements of water table elevation were taken manually until the installation of pressure transducers (miniTROLL, In Situ, Laramie, WY) in late June 2001, and periodically afterward to confirm accuracy of the transducers. A tipping bucket rain gage measured the precipitation at the top of the tower. Data from all the sensors were recorded on dataloggers (Models 21X and CR5000, Campbell Scientific, Inc., Logan, UT) which were interrogated every 7–10 days by a laptop PC. The location of the instrument tower in the mesquite woodland is shown in Fig. 1.

#### 3.2. Effect of sun angle on the IRGA

The measured densities of  $\text{CO}_2$  and water vapor exhibited unrealistic variations during 2001. These anomalous variations occurred shortly before and just after noon and they disappeared when the IRGA was mounted horizontally, suggesting they were related to the angle of the sunlight incident on the window of the IRGA's infrared source. This was confirmed by tests in which the orientation of the IRGA was changed so that sunlight was alternately directly then tangentially incident on the window of the infrared source. In the case of  $\text{CO}_2$ , the sunlight-induced signal contamination

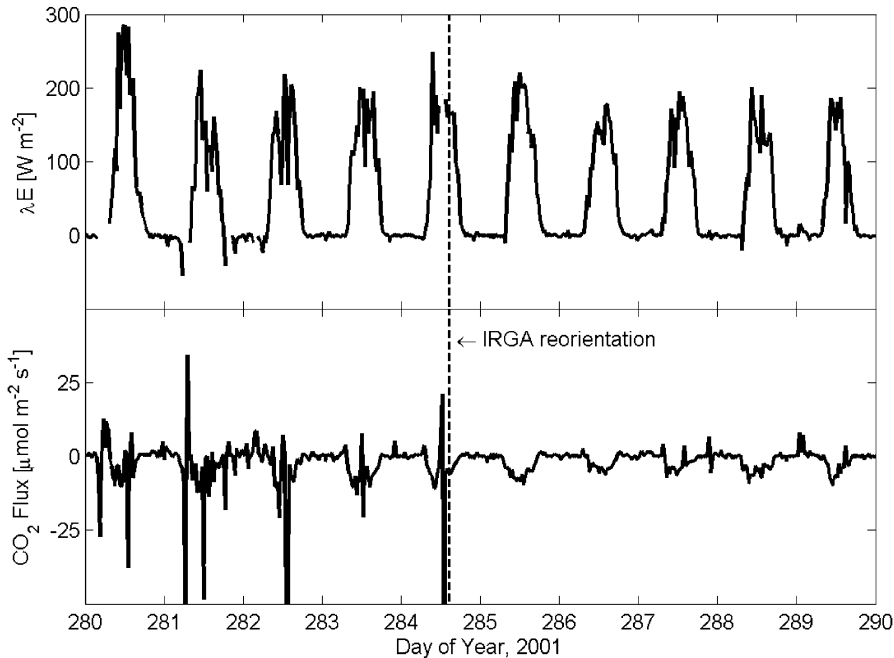


Fig. 2. Unscreened latent heat ( $\lambda E$ ) and  $\text{CO}_2$  fluxes before and after IRGA reorientation from vertical to horizontal in order to minimize the effects of sunlight shining directly into IRGA signal source window. This was prior to the sunlight effects being known and the manufacturer's modifications to correct the problem.

was as much as  $30 \text{ mg m}^{-3}$  (i.e.  $\sim 5\text{--}6\%$ ), depending on the orientation of the IRGA, while for water vapor concentration the signal contamination was up to  $0.7 \text{ g m}^{-3}$  ( $\sim 10\text{--}15\%$ ). Discovery of this instrumental weakness was reported to the manufacturer of the IRGA who issued a field note suggesting alternate mounting angles (depending on latitude) to minimize the effect of solar radiation on measured gas densities. Subsequently, the manufacturer made modifications on the IRGA to reduce the sensitivity to incident solar radiation (the sensitivity was still present, but to a lesser degree).

The sunlight-induced spikes in measured trace gas fluxes associated with the anomalous density variations just described were present in the data until 13 October 2001 when the IRGA was re-positioned horizontally. These spikes were more obvious in the measured  $\text{CO}_2$  flux than in the latent heat flux (Fig. 2). To remove the erroneous flux data, different filtering criteria were explored to diagnose when changes in the water vapor and  $\text{CO}_2$  densities measured by the IRGA were unrealistically rapid due to interference

from solar radiation. A “spike” in the variance of the  $\text{CO}_2$  density proved to be the best diagnostic. A similar relationship was found in the variance of water vapor density but, because of the greater sensitivity of  $\text{CO}_2$  measurements to solar radiation, filtering based on  $\text{CO}_2$  density was more effective. Visual inspection of the data record suggested a variance in  $\text{CO}_2$  density of  $60 (\text{mg m}^{-3})^2$  as a (conservative) indicator of when the measured  $\text{CO}_2$  and  $\text{H}_2\text{O}$  densities were effected by sunlight. Daytime fluxes calculated when the variance was above this value were removed from the data record ( $\sim 3.6\%$  of the data).

### 3.3. Turbulent Intensity

It is not uncommon for eddy covariance measurements to underestimate fluxes, especially  $\text{CO}_2$  fluxes, when turbulent intensity is low (e.g. Lee, 1998; Pilegaard et al., 2001; Turnipseed et al., 2002). Malhi et al. (1998) summarized some of the most common problems, which include the affect of horizontal advection, low frequency vertical transport, and



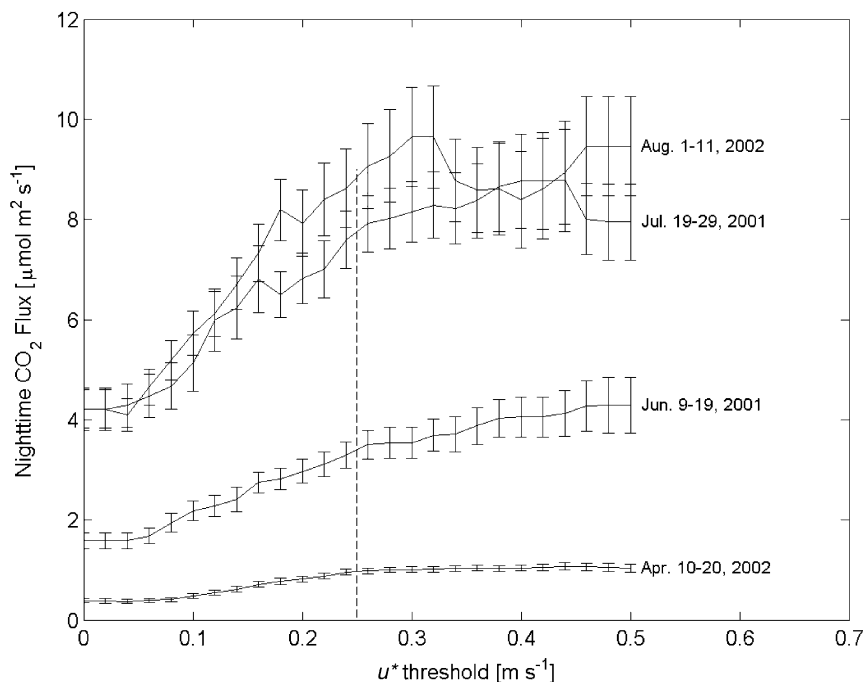


Fig. 3. Average nighttime  $\text{CO}_2$  flux ( $\pm$ S.E.) for increasing values of a  $u^*$  threshold. Values of the  $\text{CO}_2$  flux below the cutoff were excluded in each average quantity. Each line represents a sample of 10-day periods over which the nighttime temperature and surface soil moisture were fairly homogeneous.

accumulation of  $\text{CO}_2$  close to the ground at night. Recently, Gash and Dolman (2003) suggested that cosine errors in an anemometer response may also contribute, especially over tall vegetation. Several investigators have examined the effect of low turbulent intensity, as diagnosed by the friction velocity ( $u^*$ ) on the accuracy of eddy flux measurements. For example, Lavigne et al. (1997) found that nighttime  $\text{CO}_2$  fluxes obtained with the eddy covariance method were 20–42% lower than those obtained with leaf chamber measurements, but when periods of low turbulence ( $u^* < 0.25 \text{ m s}^{-1}$ ) were excluded, the agreement was much improved. Likewise, Goulden et al. (1997) excluded all periods when  $u^*$  was below  $0.2 \text{ m s}^{-1}$  and suggested that at these times  $\text{CO}_2$  “leaked” advectively from the forest. Suyker and Verma (2001) found that  $\text{CO}_2$  fluxes measured on windy nights were much less variable than on calm nights and that using only values when  $u^*$  was greater than  $0.2 \text{ m s}^{-1}$  reduced the variability of average nighttime fluxes.

To minimize the effect of poor turbulent mixing in our nighttime  $\text{CO}_2$  flux data, we restricted the analysis

to data measured when  $u^*$  was greater than  $0.25 \text{ m s}^{-1}$ . This value was determined by computing the average nighttime  $\text{CO}_2$  flux for an increasing  $u^*$  threshold for several different 10-day periods when soil moisture and temperature were fairly uniform, and when, it was assumed, nighttime respiration should be constant (Fig. 3). Unfortunately, using this filter removed 83.5% of the nighttime data, i.e. only about 15% of the nighttime flux measurements were deemed reliable and included in our analysis.

### 3.4. Flux source area

The woodland fetch was most uniform around the tower and most extensive ( $>500 \text{ m}$ ) for wind directions in the range  $10^\circ$ – $90^\circ$  and  $160^\circ$ – $270^\circ$  (Fig. 1). Outside these direction ranges, it is possible that in high winds there may have been some contamination from flux source areas with decreased tree density or even different vegetation cover. For example, 150–230 m from the tower in the angle range  $270^\circ$ – $360^\circ$ , tree cover is  $\sim 40\%$  and understory patches are more open

and frequent, while southeast of the tower, at a distance greater than 150 m, the cover changes to desert scrub. Energy fluxes originating in these regions was arguably less because the albedo was likely higher (because of a decreased tree density) and available energy less, resulting in poor energy balance closure relative to radiation measured near the tower.

Scott et al. (2003) used the flux source area model of Schmid (1994, 1997) to approximate the size of the flux source area at this site for selected days during June, August, and September 2001. Following a similar methodology to Schmid (1997), their analysis revealed that the 50% of the source area lay within 200 m of the tower for over 90% of daytime measurements, and they concluded that in light to moderate winds the tower measurements were reasonably representative of the mesquite woodland. For the flux measurements reported in this paper, average winds were similarly light (the mean wind speed was  $1.5 \text{ m s}^{-1}$  and median wind speed  $1.2 \text{ m s}^{-1}$ ), and site meteorological conditions were often within the range of the periods analyzed by Scott et al. (2003). Thus, we assumed that the tower flux measurements were representative of the woodland. Nonetheless, we do recognize that some of our measurements may have been partially contaminated by sources outside of the woodland, especially in the cases of more stable profiles (e.g. nighttime). Also, the angular dependence of the energy balance, described in the next section, suggests the consequences of an imperfect fetch may have been present in these data, and this should be kept in mind when interpreting the results.

### 3.5. Energy balance terms and closure

Neglecting the heat stored in the biomass and the air below the sensors, the one-dimensional energy balance for the mesquite woodland can be written as:

$$R_n - G = \lambda E + H \quad (1)$$

where  $R_n$  is the net radiation,  $G$  the soil heat flux, and  $\lambda E$  and  $H$  are the latent and sensible heat fluxes, respectively. As a measure of how well the energy balance was closed in our observations, Table 1 gives the results of a least squares regression between the sum of the turbulent fluxes,  $(\lambda E + H)$ , relative to the available energy  $(R_n - G)$ , for 30 min fluxes, and for daily total fluxes when fluxes were available for more than

Table 1  
Ordinary linear regression coefficients for energy balance closure

	$n$	Slope	Intercept	$R^2$
Thirty minute values				
Both years	19112	0.75	10.9	0.92
2001	9294	0.78	10.6	0.93
2002	9818	0.73	11.2	0.92
Daily means <sup>a</sup>				
Both years	452 (days)	0.82	1.9	0.90
2001	225	0.87	-1.3	0.92
2002	227	0.80	1.0	0.91

<sup>a</sup> For days with at least 24 half-hourly values of all energy balance components.

24 half-hour periods in the day. In general, closure was poor in this study with approximately 25% of the available energy unaccounted for at the hourly time scale and 18% at the daily time scale, despite the fact that the IRGA, sonic anemometer, and net radiometer were all factory calibrated before each growing season. However, this is consistent with numerous other studies made using eddy covariance instruments, see Wilson et al. (2002) for a summary of this issue. Using daily average fluxes improves the energy balance, suggesting that there was a daily cycle in the (unmeasured) energy stored in the air and particularly, the biomass below the sensors (Blanken et al., 1997; Gu et al., 1999) which was approximately 7% of the available energy.

Closure was slightly worse in 2002 than in 2001, possibly because the IRGA was re-positioned between the two years. In 2001, the IRGA was oriented with the sensor head vertical, but in 2002 the head was inclined at  $50^\circ$  with respect to north to reduce sensitivity to sunlight (see Section 3.2) and perhaps created more disturbances in wind flowing past the sensors. Fig. 4 shows the ratio  $(\lambda E + H)/(R_n - G)$  as a function of wind direction in the two field seasons. Energy balance closure was best for wind directions in the range  $160^\circ$ – $300^\circ$  and noticeably worse in 2002 for wind directions in the range  $270^\circ$ – $360^\circ$ , a range of directions where the reorientation of the IRGA may have had the most influence.

One of the goals of this study was to quantify the magnitude and variability of the seasonal water use of the mesquite woodland. It was necessary to recognize the shortcomings in closure when doing this especially since the degree of closure was significantly

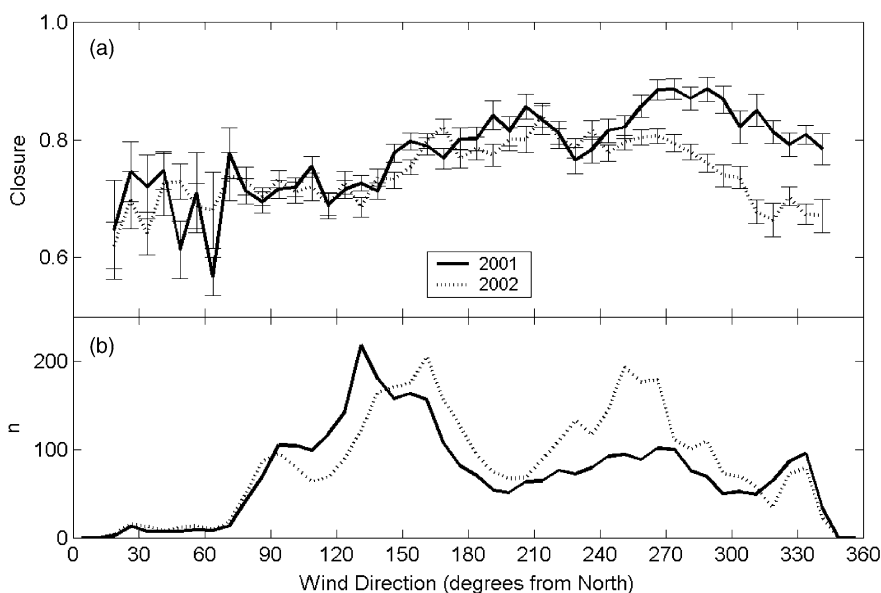


Fig. 4. (a) The effect of wind direction on closure ratio  $(\lambda E + H)/(R_n - G) \pm \text{S.E.}$  for 2001 and 2002 for wind speeds  $\geq 1 \text{ m s}^{-1}$  and for  $0.4 < (\lambda E + H)/(R_n - G) < 1.2$ . (b) Number of measurements available with wind direction for 2001 and 2002 ( $7.5^\circ$  bin size).

different between the years that we compared. For our analysis we chose to follow Twine et al. (2000), who suggested forcing closure was justified when available energy was known and errors in its measurement modest. In the current study, errors in available energy were likely similar to those of Twine et al. (2000), who estimated an uncertainty of  $\sim 10\%$  (the net radiometer used in this study was factory calibrated annually, and the annual mean available energy between 2001 and 2002 differed by just 1%). Consequently, we scaled our latent and sensible heat fluxes to force daily closure while conserving the measured Bowen ratio. Closing the daily energy balance, rather than the half-hour balance, was preferred because energy storage was unmeasured and likely significant (Table 1).

This study did not seek to quantify annual NEE because we did not make year-round measurements and there are unresolved problems when measuring nighttime carbon fluxes. However, below we did compare time-average diurnal cycles of  $\text{CO}_2$  fluxes and weekly average NEE across the growing season and between years. Twine et al. (2000) provided evidence that  $\text{CO}_2$  fluxes measured by eddy covariance were underestimated by the same factor as latent heat fluxes when energy balance closure was not achieved and Wilson

et al. (2002) also found some evidence that  $\text{CO}_2$  fluxes and energy imbalance were linked. Consequently, to be consistent with our adjustment of the latent and sensible heat fluxes, we also modified our measured  $\text{CO}_2$  fluxes in the same way as our measured latent heat fluxes, i.e. we divided the half-hour average fluxes by the daily-average energy balance closure ratio. Adjusting the  $\text{CO}_2$  fluxes in this way increased the magnitude by typically 25%, but the shape of the observed time-average diurnal cycle and the seasonal variations were conserved.

### 3.6. Missing data

In the following analysis, time-average diurnal cycles of the fluxes of water vapor and  $\text{CO}_2$  were calculated over selected periods to characterize their interannual and seasonal variability by averaging all the 30 min values available for each hour of the day. When estimating the cumulative water use during the growing season, linear interpolation was used during intermittent periods when there was missing data. In rare instances when more than 25% of the data were missing on an individual day, the daily total was estimated as being the average daily water use for the



three days before and three days after the day with missing records.

## 4. Results and discussion

### 4.1. Seasonal forcing and stand energy balance

Scott et al. (2003) used above- and below-canopy eddy covariance measurements in 2001 to show that mesquite tree water use changed little from before to after the start of the rainy season and was in good agreement with the daily groundwater drawdown. On the basis of this evidence, they concluded that the mesquite trees at this site relied mainly on groundwater as a water source, while the understory vegetation depended on recent precipitation. The spring 2002 green-up provided additional evidence that the mesquite trees relied on groundwater (Fig. 5) when there was little surface soil moisture available. The winter and spring of 2002 were very dry (Fig. 6) and surface soils were also very dry but, despite this, the trees leafed out and began to take up  $\text{CO}_2$  and lose water vapor in mid-May. At this same time, groundwater

levels began to drop and a regular pattern of diurnal drawdown (with groundwater closer to the surface in the early morning and farther from the surface at sundown) became established, providing clear evidence of a direct link between tree water use and water-table fluctuations. Because the moisture sources for the mesquite trees and understory vegetation were at least partially decoupled at the study site, seasonal changes in the partitioning of available energy between sensible and latent heat fluxes (Fig. 7) were largely controlled by just two climate factors, namely (1) spring and fall air temperatures, which controlled the length of the mesquite tree growing season, and (2) monsoon rainfall, which controlled the activity of understory plants.

Measured mid-canopy air temperature indicated that the last freezes of spring occurred on day of year (DOY) 126 in 2001 and DOY 142 in 2002, and the first freezes of fall occurred on DOY 286 in 2001 and DOY 277 in 2002 (data not shown). These freeze events effectively constrained the mesquite growing season and hence water use in the riparian corridor. The mesquite trees leafed out in the spring around the time of the last freeze. This was followed

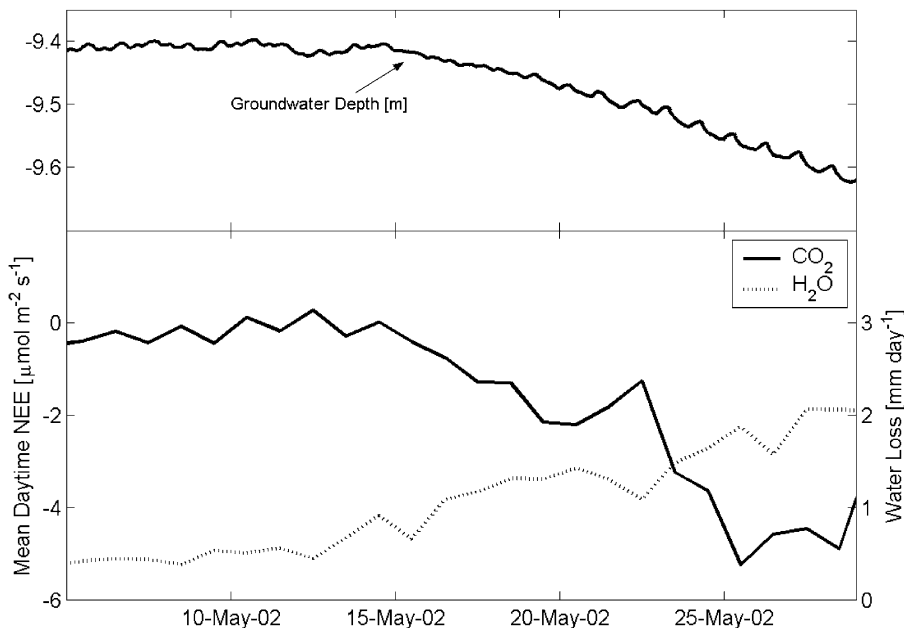


Fig. 5. Groundwater depth below surface (upper panel), average daytime NEE, and daily average evapotranspiration in May of 2002. Regular diurnal fluctuations in the water table are induced by the water uptake of tree roots.

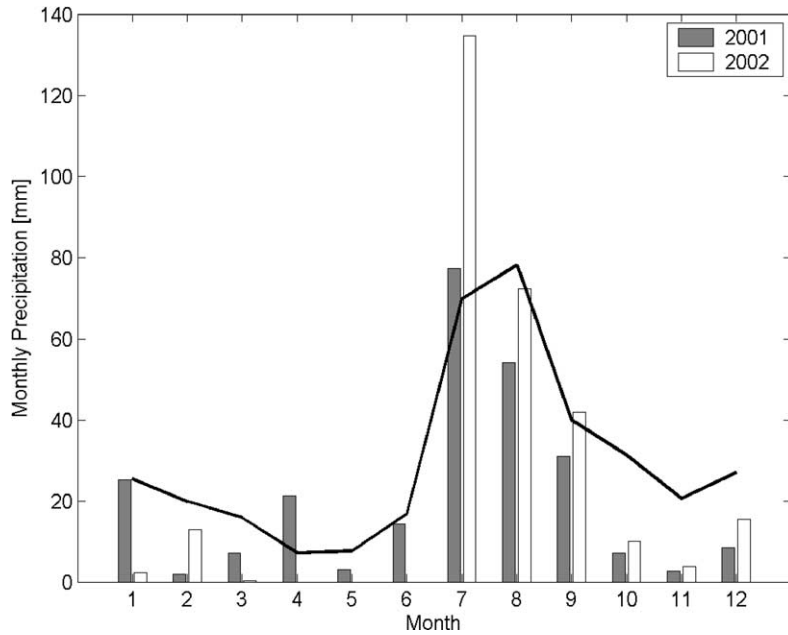


Fig. 6. 2001 and 2002 total monthly precipitation at the mesquite woodland site. For comparison purposes, the line represents 1971–2000 monthly average precipitation from nearby Tombstone, AZ.

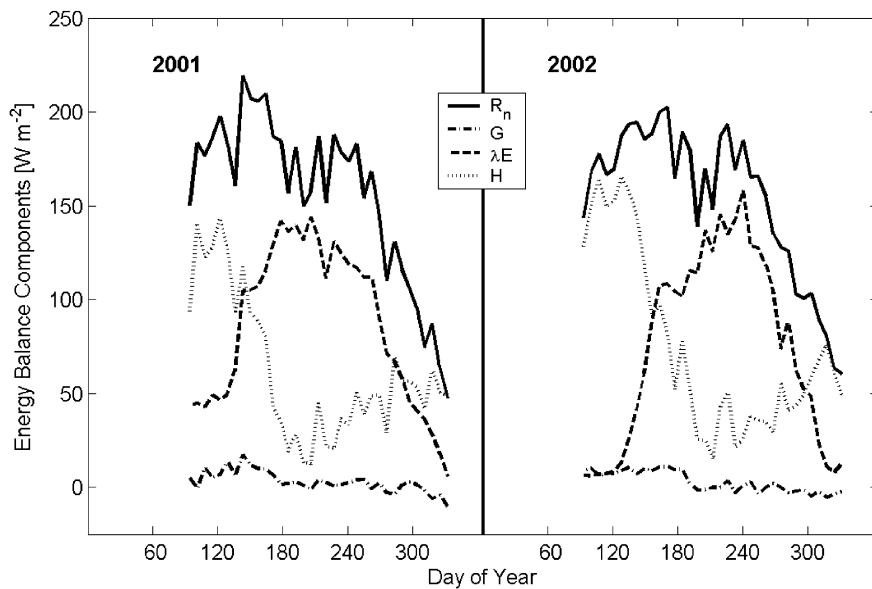


Fig. 7. 2001–2002 average weekly net radiation ( $R_n$ ), ground heat flux ( $G$ ), latent heat flux ( $\lambda E$ ), and sensible heat flux for the mesquite site.

by a substantial increase in latent heat flux, beginning around mid-May of both years (DOY 140–150, Fig. 7). Conversely, in fall, the latent heat flux dropped quickly as the mesquite trees began to senesce in late October (~DOY 300). The freeze intolerance by mesquite is consistent with studies of other temperate, ring-porous trees (McGee, 1986; Sperry and Sullivan, 1992; Lechowicz, 1995; Jaquish and Ewers, 2001). It is important to note that temperatures in the riparian corridor were often quite different from those measured above the riparian bottomland on the valley floor (data not shown). While maximum daytime temperatures agreed well, the minimum nightly temperatures were generally 5–10 °C lower in the riparian corri-

dor, except in the more humid monsoon season when the difference was less. Because the water use of the mesquite trees (and likely other riparian tree species) is constrained by the time between frosts (typically about 150 days), models of riparian evapotranspiration will require knowledge of air temperature within the riparian corridor itself, or at least estimates based on a known relationship between temperature in the riparian corridor and that measured elsewhere.

In this semiarid environment, the availability of near-surface soil moisture for understory plants was closely linked with recent rainfall (Fig. 8a). Not surprisingly, it took longer for the near-surface soil profile to dry after winter rainfall due to the lack

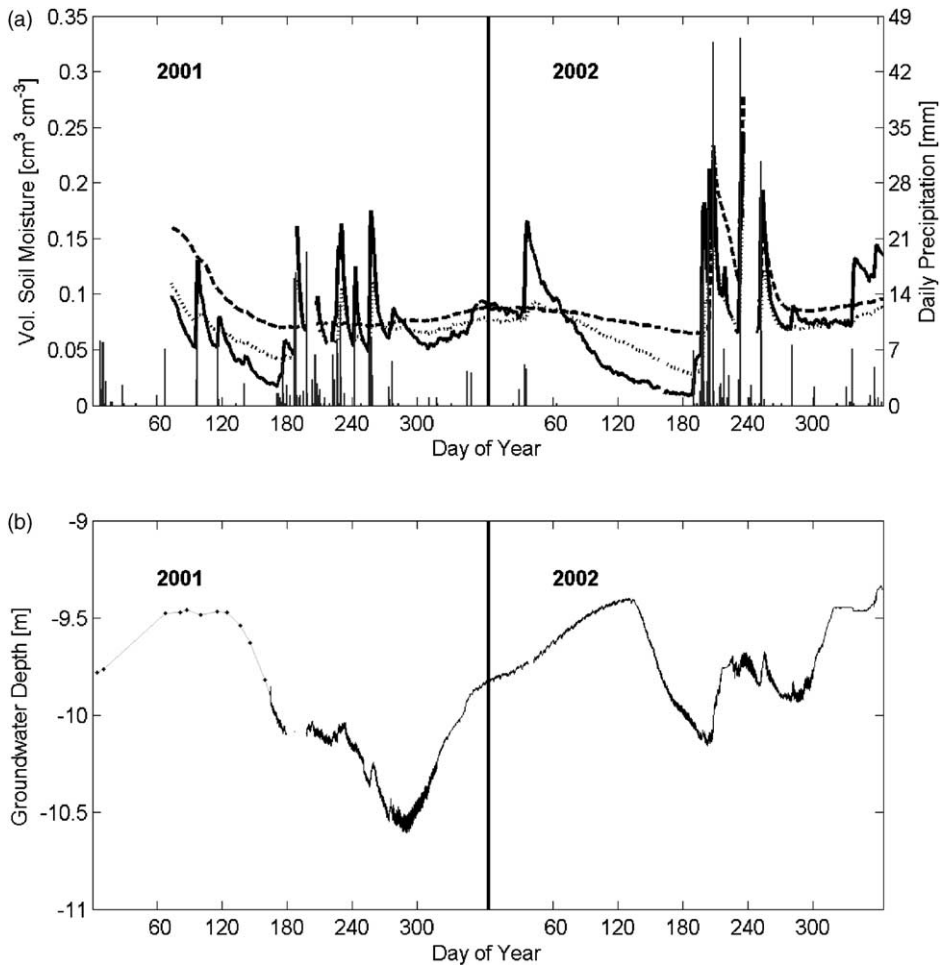


Fig. 8. (a) Daily precipitation (gray bars) with volumetric soil moisture at 5 cm (solid line), 25 cm (dotted), and 50 cm depths (dashed). (b) Groundwater depth below surface, prior to DOY 166, 2001, measurements were taken manually.

of plant uptake and decreased evaporative demand. In 2001, the effect of precipitation was rarely seen at 50 cm depth, indicating that there was little deep infiltration during much of the year and that most summer precipitation was either quickly evaporated or transpired. However, after the larger storms during the 2002 monsoon, moisture moved further down the soil profile, past 50 cm depth, although even then there was only a slight 2% increase in soil moisture at 100 cm depth (not shown). The entire root zone profile was substantially wetter in the spring of 2001, probably because there were anomalous rains totaling 125 mm in October 2000, though the origin of this soil moisture was not certain because probes were not installed until March 2001. Annual precipitation totals were 253 and 293 mm in 2001 and 2002, respectively, while the monsoon totals (i.e. the cumulative total between the mid-summer onset of precipitation and the end of September) were 177 and 248 mm in 2001 and 2002, respectively. Both of the study years had below average precipitation, but the typical pre-monsoon “drought” was especially long and severe in 2002 (Fig. 6).

In 2001 and 2002, the depth to groundwater fluctuated in response to both local and more regional forcing (Fig. 8b). Both years showed the influence of mesquite activity on water table depth with increasing depths and regular diurnal water table fluctuations beginning in late Spring (~DOY 130) in response to mesquite leaf flush, and water level recovery and no diurnal fluctuations after mesquite senescence (~DOY 300). Also, both years show complex behavior for the mid-summer monsoon period (~DOY 200–240). During this time, it is likely that water levels in this piezometer responded to both large floods passing through the nearby river channel and the mesquite supplementing tap root uptake with lateral, surface roots when and where surface water and nutrients were available. Future work will examine these interactions more in depth using a combination of additional groundwater measurements, lateral and tap root sap flow, and isotopic tracers.

Winter and spring were very dry in 2002 (Fig. 6), with the latent heat flux consistently lower than in 2001 prior to leaf-out of the mesquite trees (Fig. 7). June was the hottest and driest month and, at this time of maximum vapor pressure deficit (VPD) stress and negligible surface soil moisture; almost all the la-

tent heat flux must have been derived from mesquite tree transpiration at this time (Scott et al., 2003) and the latent and sensible heat fluxes were approximately equal. With the arrival of the summer rains, most of the available energy was lost as latent heat flux. Latent heat flux remained the dominant flux after the monsoon because there was additional near-surface moisture and the VPD stress on the trees was less, but it declined faster than net radiation as the understory dried out. The trees continued to transpire until nighttime freezing in the autumn forced their senescence and brought about a rapid reduction in latent heat flux.

#### 4.2. Diurnal latent heat and carbon dioxide fluxes

The mean diurnal cycle of latent heat and CO<sub>2</sub> during four representative periods in 2001 and 2002 were selected to characterize seasonal changes in surface fluxes during periods with similar forcing and plant activity (Fig. 9). These four periods are hereafter referred to as the “Spring”, “Pre-Monsoon”, “Monsoon”, and “Autumn” periods. The dates used to define the periods and site conditions during each are given in Table 2. The Spring and Autumn periods characteristically had mean daily temperatures below 19 °C and saw little precipitation. The Pre-Monsoon and Monsoon periods had mean temperatures above 23 °C, with the Monsoon period corresponding to the summer rainy season. During the Spring period, the mesquite trees had not yet leafed but some perennial grasses in the understory did show some green blades in 2001. During the Pre-Monsoon period, only the trees were green, while during the Monsoon period, the understory was also lush and green. The mesquite leaves remained active during the Autumn period but the understory was by then largely senescent.

The daily cycle of latent heat flux varied significantly within and between growing seasons (Fig. 9a). The most noticeable differences between 2001 and 2002 were in the Spring and Pre-Monsoon periods. As previously mentioned, in the spring of 2001 prior to tree leafout the near-surface soil was much wetter than in 2002, and the latent heat flux was higher due to understory evapotranspiration. The drought-like conditions of 2002 continued into the Pre-Monsoon period. In both Pre-monsoon periods, the latent heat flux peaked before mid-day, suggesting that the trees were

Table 2  
Description of periods over which average diurnal patterns were compared

Period	Year	Time span	Typical conditions	Ppt <sup>a</sup>	T <sup>b</sup>	VPD <sup>c</sup>	θ <sup>d</sup>
Spring	2001	10 April–5 May	Cool, little precipitation, pre-bud burst	8.6	16.5	1.6	0.08
	2002	10 April–5 May	Cool, little precipitation, pre-bud burst	0	18.0	1.9	0.03
Pre-monsoon	2001	1–20 June	Hot, very dry, maximum VPD > 5–6 kPa	0	24.0	2.7	0.03
	2002	1–20 June	Hot, very dry, maximum VPD > 5–6 kPa	0	25.6	3.0	0.02
Monsoon	2001	1–26 August	Hot, abundant monsoon precipitation, lower VPD	44.2	23.8	1.2	0.04
	2002	1–26 August	Hot, abundant monsoon precipitation, lower VPD	68.1	23.9	1.3	0.05
Autumn	2001	1–26 October	Post-monsoon, cooler, trees still leafed	6.9	16.5	1.2	0.04
	2002	1–26 October	Post-monsoon, cooler, trees still leafed	7.6	16.1	1.2	0.04

<sup>a</sup> Total precipitation (mm) within the period.

<sup>b</sup> Average air temperature (°C).

<sup>c</sup> Average vapor pressure deficit (kPa).

<sup>d</sup> Average volumetric water content at 5 cm.

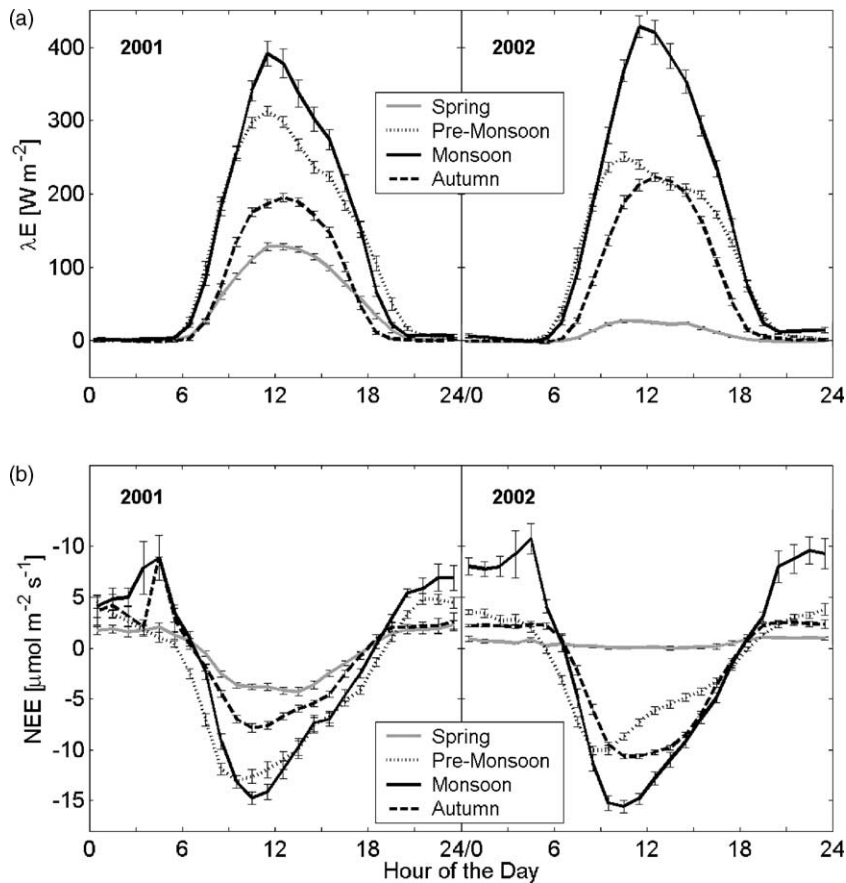


Fig. 9. (a) Mean diurnal cycles of (a) latent heat flux and (b) CO<sub>2</sub> flux for four seasonal periods during 2001 and 2002: Spring (gray line), Pre-Monsoon (dotted line), Monsoon (solid line), Autumn (dashed line). The bars indicate  $\pm$ S.E. of the bin-averaged values. See Table 2 for period definitions. Negative values of CO<sub>2</sub> flux indicate net uptake by the ecosystem.

regulating their stomata to limit water loss. In 2002, the peak flux occurred an hour earlier, corresponding to a shift of VPD toward higher values earlier in the morning (data not shown). Stomatal closure due to high VPD levels has been observed in other regions that experience growing season drought (Meinzer et al., 1993; Monteith, 1995; Williams et al., 1998). Notwithstanding the noise that was presumably in part a response of stomata to other forcing variables (e.g. temperature, radiation, groundwater levels), there was a clear relationship between canopy resistance and VPD in both years (Fig. 10, upper panel). In practice, this stomatal response when acting in combination with the VPD-induced atmospheric demand resulted in a noticeable decrease in water loss when the VPD was greater than  $\sim 3$  kPa (Fig. 10, lower panel). Along with a lower canopy resistance, the maximum latent heat flux in the Pre-Monsoon period was, on average, greater in 2001, reflecting the trees' drought-related water stress and the reduced LAI, which was measured in June as  $1.6 \pm 0.1$  in 2001 and  $1.3 \pm 0.1$  in 2002.

Given that the trees did have access to the groundwater and that the water table depths were not deeper in 2002 (Fig. 8b), we do not know at this time why the trees would be more stressed then. Preliminary root sap flow data on lateral and tap roots of the trees at this site suggest that the trees redistributed moisture both upwards and downwards depending on surface soil moisture status, similar to what was found by Hultine et al. (2003). We speculate that the trees' greater stress in 2002 was possibly due to the more abundant, nutrient-rich, surface moisture in the spring of 2001 that preconditioned the trees to put on a greater leaf area, or perhaps the trees used an additional 1–10 m vadose zone water source which was redistributed there via roots during the large rains of October 2001. Alternatively, the more drought-like conditions in 2002 may have caused loss of conductivity in the mesquite stems via drought-induced embolism as has been observed in other ring-porous trees (Jaquish and Ewers, 2001).

Similar diurnal patterns of latent heat flux were observed in both years in the Monsoon and the Autumn

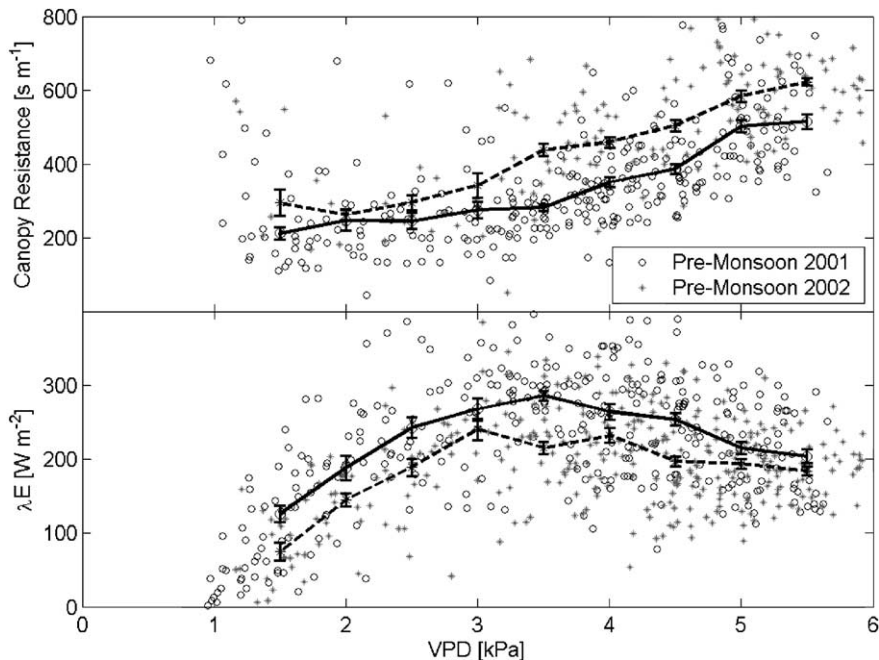


Fig. 10. Daytime vapor pressure deficit vs. canopy resistance (upper panel) and latent heat flux (lower panel) for the 2001 (circles) and 2002 (asterisks) during the Pre-Monsoon period. Also shown are the 2001 (solid line) and 2002 (dashed line) bin-averaged results ( $\pm 0.25$  kPa). The bars indicate  $\pm$ S.E. of the bin-averaged values. Canopy resistance was calculated using the inverted Penman–Monteith equation, following the methodology used by Wever et al. (2002). The mesquite trees were clearly limiting their water loss above  $\sim 3$  kPa, and the trees showed signs of additional drought stress during 2002.



periods as the herbaceous and perennial grass cover responded quickly to the monsoon precipitation. This understory response and the decreased stomatal shut-down on the trees resulted in a greater latent heat flux in the Monsoon period (Fig. 9a). The latent heat flux fell in both Autumn periods as the available energy decreased and the annual vegetation in the understory dried out, but the Autumn latent heat flux was a little higher in 2002, presumably because the monsoon rainfall was higher (Fig. 6).

Mean diurnal cycles of  $u^*$ -filtered  $\text{CO}_2$  flux (Fig. 9b) were closely related to those of latent heat flux during the daytime and also showed marked changes through the season and between the 2 years. The higher soil moisture in spring 2001 led to a partially active understory and greater  $\text{CO}_2$  uptake as compared to spring 2002. Because the understory was largely senescent in the Pre-Monsoon periods, daytime  $\text{CO}_2$  uptake was mainly by the trees. During this period, the effect of the stomatal response revealed in the diurnal cycle of latent heat was also apparent in the  $\text{CO}_2$  flux. The shift in peak flux was 2 h earlier for NEE than for latent heat flux. The carbon uptake pattern directly reflected when the trees started to close their stomata partly in response to rising VPD, but the higher VPD (atmospheric demand) partially compensated in the case of latent heat. The reduced maximum Pre-Monsoon uptake of  $\text{CO}_2$  in 2002 is further evidence that the trees were more drought stressed than in 2001.

Nighttime NEE is a measure of ecosystem respiration and the data suggested that there was a small but measurable release of  $\text{CO}_2$  at night during the Spring and Pre-monsoon periods, although it is important to bear in mind the potential errors in observed fluxes due to the paucity of flux data above the  $u^*$  threshold (discussed in Section 3.3). This nighttime release was most likely due to tree respiration because the surface soil was very dry.  $\text{CO}_2$  fluxes were large and negative during the day and large and positive during the night in Monsoon periods because precipitation provided moisture not only to grow the understory vegetation, but also to stimulate soil respiration. In fact, assuming the  $u^*$ -filtered nighttime data were reliable, increased respiration during the Monsoon periods reduced the net daily-average  $\text{CO}_2$  flux by 1.7 and  $1.1 \mu\text{mol m}^{-2} \text{s}^{-1}$  in 2001 and 2002, respectively, relative to Pre-Monsoon levels despite the marked increase

in daytime carbon uptake. The fact that net ecosystem carbon uptake decreased with the arrival of summer rainfall, even though the understory became active at this time, is a strong indication that microbial respiration was severely water-limited at this site and only occurred for short periods after precipitation, whereas the mesquite trees, with ready access to groundwater, were able to take up carbon throughout the summer season. During the Autumn period, both daytime and nighttime exchanges were reduced as the drying surface soil reduced uptake by understory herbs/grasses and inhibited microbial respiration.

The seasonal pattern of daytime and nighttime  $\text{CO}_2$  fluxes in this ecosystem type highlights an important control over ecosystem—atmosphere exchanges. The magnitude and seasonal activity of ecosystem respiration significantly influences seasonal and year-to-year variation in net carbon accumulation. The percent increase in gross photosynthetic activity (NEE—nighttime  $\text{CO}_2$  efflux) was similar between the pre-monsoon and monsoon periods for each year of the study at about 150%. In contrast the percent increases in respiratory activity were 180% in 2001 and 270% in 2002. In other ecosystem types, this control of ecosystem respiration over  $\text{CO}_2$  fluxes has been attributed to differential effects of temperature on gross photosynthetic and respiratory activity (Valentini et al., 2000; Huxman et al., 2003). In the current ecosystem type, differences in the seasonal dynamics of water sources driving photosynthetic and respiratory activity (groundwater versus summer rainfall) had a similar effect. This trend highlights an additional mechanism by which ecosystem processes can be decoupled and significantly affect carbon cycling (Huxman et al., 2003).

#### 4.3. Seasonal water and carbon dioxide fluxes

Law et al. (2002) reported that only 2 out of the 35 FLUXNET sites in their analysis had an annual evaporation greater than precipitation. Because the mesquite trees had access to the groundwater ~10 m below the surface, more water left the ecosystem as evaporation than entered as precipitation during 2001 and 2002 (Fig. 11). The total evaporation amounts during the (equivalent) measurement periods in 2001 and 2002 were 744 and 645 mm, respectively. Evaporation was less in 2002 because the much drier

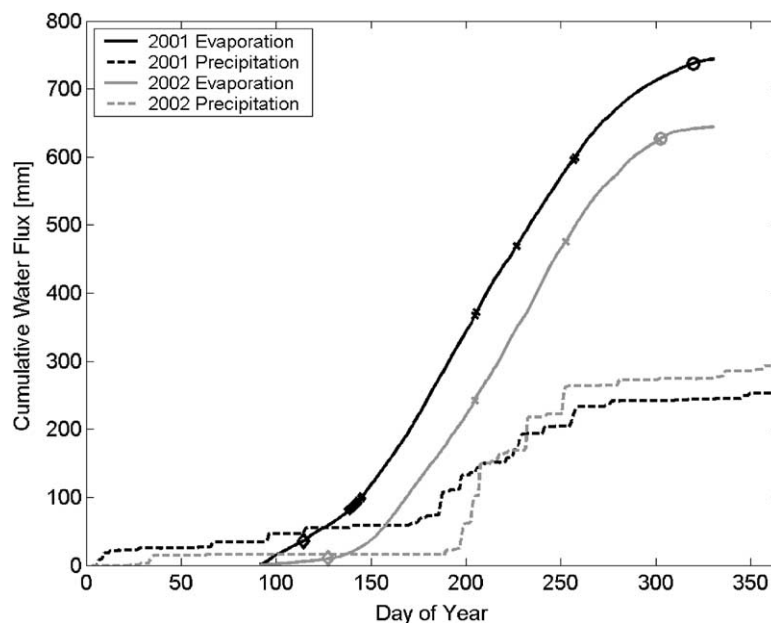


Fig. 11. Cumulative fluxes of precipitation and evapotranspiration for 2001 and 2002. Interpolated values are indicated with an “x”. The last freeze of spring is indicated by a diamond and the first freeze of autumn is indicated by a circle. *Note:* evapotranspiration data were only available from 1 April to 28 November of each year.

conditions at the time of mesquite tree leafout meant there was less evaporation (mainly transpiration) in the 2002 Pre-monsoon period. At the time of tree leafout (~DOY 140, in both years), 66 mm more water had evaporated by the understory in 2001 than 2002, and the average evaporation before the monsoon, i.e. over the period DOY 150–170, was 4.0 mm per day in 2001 and 3.4 mm per day in 2002. The monsoon rain arrived 20 days later in 2002.

An important goal of this study was to estimate the total groundwater use of the mesquite ecosystem. We can use the total evaporation, shown mainly to be transpiration by Yopez et al. (2003), minus precipitation and soil moisture storage change as an estimate of the groundwater use by the mesquite trees for the entire growing season. We assumed that runoff from the woodland was negligible as there were no flow channels evident. It is likely that the well-covered surface and porous, sandy soil quickly absorbed any infiltration-excess runoff generated on less permeable surfaces. Over the period DOY 121–332, evaporation exceeded the sum of precipitation and change in soil moisture by 488 mm in 2001 and 394 mm in 2002, corresponding to an average mesquite tree *groundwa-*

*ter* use of 2.3 mm per day in 2001 and 1.9 mm per day in 2002. Preliminary well, root sap flow, and isotopic data not shown in this paper indicated that the mesquite did supplement their water use with some surface moisture when it was available so it is likely that the *total* mesquite evaporation was higher than these totals.

The net CO<sub>2</sub> and water vapor fluxes were only partly linked in this mesquite woodland ecosystem (Fig. 12). The general pattern of fluxes was similar in both years, although they did exhibit differences which were likely induced by climate. As previously stated, evapotranspiration showed only limited sensitivity to monsoon rainfall because the mesquite trees, the dominant component of the ecosystem, relied mainly on groundwater. However, soil moisture dramatically affected nighttime respiration and rainstorms generated large increases in respiration that then gradually decreased as the surface soil dried. Because the mesquite trees were generally not water-limited, they fixed carbon throughout the growing season, while the activity of understory plants and microbes were strongly determined by recent precipitation. The carbon absorbed by the trees ultimately appears in the form of an

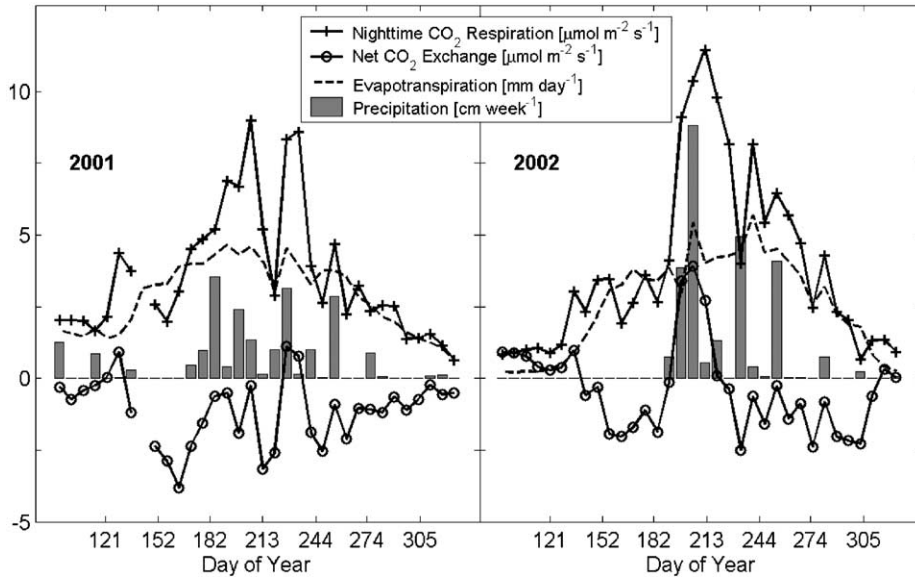


Fig. 12. Weekly average water and CO<sub>2</sub> fluxes for 2001 and 2002. Net CO<sub>2</sub> exchange (NEE) was calculated as the day-length weighted sum of the weekly average daytime and nighttime CO<sub>2</sub> fluxes. Negative values of CO<sub>2</sub> flux indicate net uptake by the ecosystem.

abundant litter layer and fine roots that fuel substantial carbon releases by microbial activity after rain. The net effect of these competing processes was apparent in the weekly CO<sub>2</sub> exchange (Fig. 12). Although the ecosystem was a net sink of atmospheric CO<sub>2</sub> through most of the growing season, large respiration fluxes did reverse the balance and result in a net loss of CO<sub>2</sub> when the monsoon was most active. Also, the strong respiration response in 2002 following the springtime drought is consistent with Fisher and Whitford (1995), who suggested that first substantial rains following a drought period will induce a particularly strong soil respiration response.

It is important to reiterate the need for caution when interpreting the CO<sub>2</sub> flux data presented here. We relied on time averaging to provide a realistic picture of the behavior of ecosystem, but the measurements of nighttime CO<sub>2</sub> fluxes were not necessarily reliable. Recall that 85% of the data were excluded because they were taken when turbulent intensity was low, and some weekly average fluxes were therefore calculated from very limited data. It is nonetheless reassuring that the average diurnal and weekly patterns did appear self-consistent and give an intriguing, but plausible, picture of carbon exchange for the mesquite woodland ecosystem.

## 5. Summary and conclusions

Near-continuous eddy correlation measurements of surface exchange fluxes were obtained during the 2001 and 2002 growing seasons for a riparian mesquite woodland in the semiarid climate of southern Arizona. The functioning of the ecosystem changed substantially through each year in response to climatic conditions, most noticeably in response to freezing temperatures, high vapor pressure deficit, and precipitation. Within the growing season, the most significant change occurred with the arrival of mid-summer monsoon rainfall, which dramatically altered the climate forcing and strongly impacted understory fluxes. During summer before the monsoon, when afternoon temperatures and vapor pressure deficits were high, the afternoon reduction in latent heat flux and net carbon uptake suggested that the mesquite trees were acting to reduce their water loss through stomatal regulation. The arrival of monsoon precipitation stimulated green-up of the annual herbs and perennial grasses beneath the forest canopy, and the increase in near-surface soil moisture led to increased evapotranspiration and daytime carbon assimilation. However, there was a decrease in net daily carbon uptake relative to values observed before the monsoon levels

because the increase in respiration at night exceeded the increase in uptake during the day.

Variability in climatic forcing between the two years of the study amplified the seasonal pattern just described. The winter/spring drought led to very low understory evapotranspiration, daytime carbon uptake, and nighttime soil respiration prior to the mesquite tree leaf out in 2002. After leafout and during the pre-monsoon season in 2002, the mesquite trees showed a partial response to high vapor pressure deficit similar to that seen in 2001, but canopy conductances and latent heat fluxes were consistently lower, probably as a consequence of a decrease in leaf area. Thus, the mesquite trees appeared to be transport limited in their water use under high atmospheric demand and to be negatively impacted by drought conditions even though groundwater fluctuations showed that they continued to have access to a stable source of water throughout the growing season. The higher monsoon precipitation in 2002 resulted in greater latent heat fluxes from additional understory evapotranspiration. Assuming the CO<sub>2</sub> fluxes measurements were reliable, the mesquite woodland ecosystem appeared to be a net sink of CO<sub>2</sub> for most of the growing seasons, but abundant monsoon precipitation temporarily reversed the balance to give a net loss of CO<sub>2</sub>.

In order to provide information that is useful from a water resources standpoint, future work will entail the development of an evapotranspiration model to predict the water use of mesquite woodlands and other similarly functioning, phreatophytic ecosystems. This model will need to disaggregate groundwater uptake from total evapotranspiration and respond appropriately to changing boundary conditions. In order to do this, additional studies are being carried out to understand what are the key forcing variables that determine *seasonal* evapotranspiration and how to partition it into groundwater and surface water sources.

## Acknowledgements

This work is supported in part by Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA) 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 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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