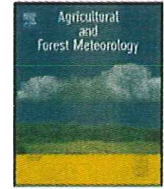


Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

Journal homepage: www.elsevier.com/locate/agrformet



Evapotranspiration and energy balance of Brazilian savannas with contrasting tree density

Thomas W. Giambelluca ^{a,*}, Fabian G. Scholz ^b, Sandra J. Bucci ^b, Frederick C. Meinzer ^c, Guillermo Goldstein ^{d,e}, William A. Hoffmann ^f, Augusto C. Franco ^g, Martin P. Buchert ^{a,h}

^a Department of Geography, University of Hawaii at Mānoa, Honolulu, HI 96822, USA

^b Comisión Nacional de Investigaciones Científicas y Técnicas (CONICET), Facultad de Ciencias Naturales, Universidad Nacional de la Patagonia San Juan Bosco, 9000 Comodoro Rivadavia, Argentina

^c USDA Forest Service, Forestry Sciences Laboratory, 3200 SW Jefferson Way, Corvallis, OR 97331 USA

^d Department of Biology, University of Miami, P.O. Box 249118, Coral Gables, FL 33124, USA

^e CONICET and Laboratorio de Ecología Funcional, Universidad Nacional de Buenos Aires, Departamento de Ecología, Genética y Evolución, Pabellón II, Ciudad Universitaria, Buenos Aires, Argentina

^f Department of Plant Biology, Campus Box 7612, North Carolina State University, Raleigh, NC 28695-7612, USA

^g Departamento de Botânica, Universidade de Brasília, Caixa Postal 04457, Brasília, DF 70904-970, Brazil

^h H.W. Lochner, Inc., 310 East 4500 South, Suite 600, Murray, UT 84107, USA

ARTICLE INFO

Article history:

Received 28 October 2008

Received in revised form 5 March 2009

Accepted 15 March 2009

Keywords:

Tropical savannas

Land-atmosphere interaction

Leaf area index

Soil moisture

ABSTRACT

Tropical savannas including those of central Brazil (Cerrado) serve as an important regulator of energy and mass exchange with the atmosphere. However, the effects of interactions between grasses and deeply rooted trees and shrubs on energy and water fluxes of savannas are not well understood. In this study, eddy-covariance measurements were used to observe and compare the energy balance and evapotranspiration at two adjacent Cerrado sites differing in woody plant density.

Latent energy flux (LE) and evapotranspiration (ET) for Cerrado Denso (8–10-m trees with a cover density of approximately 50% and an understory of grass and shrubs) were generally similar to those of Campo Cerrado (widely scattered 3–4-m trees with a cover density of about 5% and an understory of grasses, shrubs, and sedges), with the greatest difference between the sites occurring during the dry season. Mean annual ET was 823 and 689 mm yr⁻¹, and LE averaged 63.9 ± 11.7 and 53.5 ± 14.3 W m⁻² at Cerrado Denso and Campo Cerrado, respectively. At both sites, ET reached a minimum at near the end of the dry season, indicating that reduced water availability constrained dry season ET at both sites. The Bowen ratio at both sites increased as soil moisture decreased, but with a stronger dependency at the Campo Cerrado site, presumably due to the dominance of shallow-rooted plants and the larger contribution of soil evaporation there. Energy partitioning, as indicated by the Bowen ratio, was also strongly influenced by variations in leaf area index (LAI). The strong similarity in the Bowen ratio-LAI relationship for the two sites suggests that LAI can be used to explain much of the observed temporal and spatial ET variability across seasons and variations in woody plant density in the Cerrado.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

Tropical savannas cover about one-eighth of the global land surface (Scholes and Archer, 1997) and are characterized by high plant species diversity. According to FAO (1993), livestock grazing on tropical savannas is the world's most extensive land use. The 1960s, however, marked the beginning of the expansion of large-scale agriculture and planted pastures across the savannas of central Brazil (Cerrado), and the region is now one of the world's largest soybean and beef producers. Despite its extent, biotic

richness, and vulnerability to impacts of human activities, this biome has received relatively little attention from researchers in comparison with tropical rain forests. Savanna covers about 45% of the area of South America (Scholes and Archer, 1997), most of which is comprised of the Cerrado. The Cerrado is an important regulator of energy and mass exchange with the atmosphere (Miranda et al, 1997). However, the interactions between grasses and deeply rooted trees and shrubs and the effects of these interactions on energy and water balances are not well understood (Meinzer et al, 1999).

Neotropical savannas, and in particular the Cerrado, contain a mixture of many tree and herbaceous species having different responses to variations in environmental conditions. The climate is extremely seasonal with about five rainless months and a long

* Corresponding author.
E-mail address: thomas@hawaii.edu (T.W. Giambelluca).

period with high rainfall. Evaporative demand is substantially higher during the dry season when environmental conditions induce plant water stress in the shallow-rooted herbaceous species and for some relatively shallow-rooted woody species. In contrast, most trees have deep roots capable of tapping abundant and stable soil water resources (Scholz et al., 2008). Meinzer et al. (1999) showed that seasonal variations in plant water status of deeply rooted trees and shrubs are relatively small and that their maximum transpiration rates are not severely limited by seasonal variation in soil moisture. The herbaceous layer, including many C4 and C3 grasses, loses a substantial fraction of its leaf area during the peak of the dry season. Evidence of hydraulic redistribution, transport of water from wet to dry soil layers via the roots of woody plants, has also been consistently found in cerrado ecosystems (Scholz et al., 2002, 2008; Moreira et al., 2003; Meinzer et al., 2004). Upward water transport via this process may help maintain transpiration in herbaceous plants during the dry season. Because of the high species diversity and complex interactions among different plant functional groups in the Cerrado, it is difficult to predict ecosystem mass and energy exchanges based on measurements at the individual plant level.

Relatively few studies have employed eddy covariance techniques to characterize energy and water vapor fluxes in tropical savannas. A common denominator among the findings of the few available studies is the strong decline in latent heat flux during the dry season as the herbaceous layer senesces (Miranda et al., 1997; Eamus et al., 2001). An additional pattern observed across studies is the seasonal change in the mode of dissipation of available energy, with similar amounts being dissipated via sensible and latent heat loss during the wet season, and with a large increase in sensible heat loss during the dry season (Miranda et al., 1997; Hutley et al., 2001; Santos et al., 2003). The savannas of central Brazil exhibit consistent changes in tree density along shallow topographic gradients and also due to fire frequency. Consequently, if mass and energy exchange are to be characterized for the Cerrado region, the measurements have to capture the seasonal changes and the changes across spatial variations in tree density.

As part of a comprehensive study of the partitioning of soil water between herbaceous and woody plants, and the impact of hydraulic redistribution on ecosystem water cycles, we undertook a field study of two Cerrado sites differing in woody plant density. The first three objectives of the work presented here relate to improving understanding of spatial and temporal patterns of evapotranspiration within the Cerrado. Specifically, they are to (1) observe and compare the energy balance and, in particular, evapotranspiration (i.e. the latent heat flux) at two adjacent cerrado sites with contrasting woody plant density using eddy covariance methods; (2) determine the effects of the seasonal change in moisture availability on energy and water fluxes at the two sites; and (3) examine the diurnal patterns of evapotranspiration at the two sites for evidence of stomatal regulation during the rainy and dry seasons. Eddy covariance, while the preferred approach for studies of ecosystem energy exchange and evapotranspiration, requires expensive, high-maintenance instrumentation. Therefore, we include an additional objective to (4) evaluate an alternative to eddy covariance for estimating energy and water fluxes in Cerrado vegetation.

2. Methods

2.1. Site description

Vegetation in the Cerrado region ranges from dense forest to open grassland, but savanna physiognomies dominate. The latter includes four principal physiognomic types differing mostly in tree density and height: *cerradao*, a medium to tall woodland with

a closed or semi-closed canopy: *cerrado sensu-stricto*, a savanna with abundant evergreen and brevi-deciduous trees and an herbaceous understory; *campo cerrado*, an open savanna with scattered trees and shrubs and *campo sujo*, open savanna with scattered shrubs. Cerrado *sensu stricto* is often subdivided into *cerrado denso* (dense), *cerrado tipico* (typical), and *cerrado ralo* (thin) subtypes of decreasing tree density and height. Cerrado landscapes are mosaics of these vegetation types grading continuously from one to another over distances of tens of meters to several kilometers. Field measurements for this study were made at two sites within the IBGE (Instituto Brasileiro de Geografia e Estatística) ecological reserve, a field experimental station located approximately 33 km south of the center of Brasília (15°56'S, 47°53'W) at approximately 1100 m elevation. Mean annual rainfall, 1440 mm, is highly seasonal with 85% falling during October through March. The range of mean monthly air temperature is very narrow, with a minimum of 20.1 °C in June and a maximum of 23.5 °C in October. Duration of bright sunshine is high during the dry season, peaking in July, and low in the wet season, with a minimum in December. Rainfall, temperature and sunshine duration are based on measurements at IBGE weather station for 1980–2004 (<http://www.recor.org.br/cerrado/clima.html>).

Our two sites were situated within different cerrado physiognomies based on woody plant density. One tower was located in a Cerrado Denso stand, characterized by 8–10-m trees with a cover density of approximately 50% (~2800 trees ha⁻¹), and an understory of grasses and shrubs. Regarding fetch, winds at IBGE are predominantly NE during the day and SE at night. Cerrado Denso vegetation was relatively uniform for distances of approximately 600–750 m from the tower within the NE to SE quadrant. Similar or greater fetch distances were found in all other directions except S, where tree height and density decreased somewhat within about 300 m.

A second tower was located about 950 m southwest of the first tower within Campo Cerrado vegetation, with shrubs and widely scattered 3–4-m trees with a cover density of approximately 5% (~1700 trees and shrubs ha⁻¹), with an understory of grasses and sedges. Just to the south of this tower, tree density is lower, while approximately 250–500 m to the NE, vegetation maps for the area show a transition to Cerrado Denso vegetation. In reality, the tree height and density gradually decreases along a NE–SW line running through the site. However, because of the gradation in vegetation around this tower, fetch issues become more important. During the day, with NE winds, the footprint for this station extended toward somewhat taller, denser vegetation; while at night, with SE winds, the footprint shifted toward shorter, sparser vegetation. Fetch issues will be discussed with respect to flux measurements at both sites.

The soils are deep oxisols consisting of about 72% clay. Despite their high percentage of clay, the soils behave as coarser-textured soils and are extremely well drained. Analyses of soil physical properties, done by the soil laboratory of the Agricultural Research Center for the Cerrado region (EMBRAPA, Brazil) were previously reported by Bucci et al. (2008). Water retention curves for nearby sites within IBGE, in Campo Sujo and Cerrado Denso vegetation were given by Oliveira et al. (2005). Root profile data show that 92% of fine root mass in both Campo Sujo and Cerrado Denso sites was found in the upper 1 m soil layer, and that the distribution of roots in the upper 3 m was similar for the two sites (Oliveira et al., 2005). Roots are thought to extend to much greater depths. Based on multi-sensor frequency domain capacitance probe data for the sites, soil moisture drawdown between the maximum wet season storage and the minimum dry season storage was 155 mm for the upper 3 m, and 99 mm for the upper 1 m (64% of the 3-m total) at the Cerrado Denso site, and 126 and

113 (84%) for the 0–3 and 0–1 m layers, respectively at the Campo Cerrado site. See Meinzer et al. (2004) for a description of the capacitance probe measurements.

2.2. Field measurements

2.2.1. Leaf area index

Leaf area index (LAI) was measured using a plant canopy analyzer (LAI 2000, LI-COR Inc., Lincoln Nebraska, USA), which estimates LAI based on attenuation of light by the canopy at various angles. For the herbaceous/subshrub layer, total plant area index (green + brown material) was estimated by making consecutive measurements above and below the herbaceous layer. The fraction of the plant area index consisting of various components - green monocot leaf, green dicot leaf, brown monocot leaf, and brown dicot leaf and stem - was determined for each date by counting points of contact between each component and a rod placed vertically at 80 locations in the herbaceous layer (Hoffmann et al., 2005). Tree and shrub LAI was estimated by making measurements with the LAI 2000 under woody plants with a minimum height of 1 m. Subsequently, the LAI estimate was multiplied by the fractional tree and shrub cover to obtain the area-averaged LAI. The fractional tree cover was estimated in each vegetation type by characterizing the vegetation at 1-m intervals along ten 50-m transects. A point was considered to have tree or shrub cover if a vertically placed telescoping pole passed through the convex polygon circumscribed by the crown of at least one woody plant with height > 1 m. See Hoffmann et al. (2005) for details.

2.2.2. Eddy covariance and related measurements

A single set of eddy covariance sensors was moved back and forth between the two sites, remaining at each location for approximately three to five weeks during the June 2001 through June 2003 study period. Three-dimensional wind velocity (uvw) was measured using a sonic anemometer (CSAn, Campbell Scientific; Logan, UT, USA). Rapid fluctuations in humidity (q) were monitored using a krypton hygrometer (KH20, Campbell Scientific). Air temperature fluctuations were obtained from the sonic anemometer (T_{sonic}) and from a fine-wire thermocouple (T_{fw}). These sensors were mounted above the canopy at each site, in close proximity to each other. See Table 1 for sensor heights. A data logger (CR5000, Campbell Scientific) was used to record raw sensor output at 20 Hz and to estimate fluxes of sensible and latent energy (H and LE). Raw eddy covariance data were stored on 2-Gbyte PCMCIA hard drives (Kingston Technology Co., CA, USA), which were supported by the CR5000 data logger. Downward and upward shortwave radiation (K_d and K_u) were also measured alternately at each site using two Eppley (Newport, RI, USA) 8–48 pyranometers mounted facing up and down, respectively. Other supporting meteorological measurements were made continuously at the two sites throughout the study period. Above-canopy

measurements (Table 1) included net radiation (R_{net}), using net radiometers ($Q^*7.1$, REBS, Bellevue, Washington, USA), air temperature (T_{air}) and relative humidity (RH), using Vaisala (Helsinki, Finland) HMP45C sensors, and horizontal wind speed (WS) and direction (WD), using MetOne (Grants Pass, OR, USA) 034A anemometer/vane units. Rainfall was measured at each site, but because of gaps in the records, rainfall measured at the nearby IBGE weather station is reported here. Soil heat flux at the soil surface was estimated at each site as:

$$G = F + M$$

$$F = \frac{SHF_1 + SHF_2 + SHF_3 + SHF_4}{4} \quad (1)$$

$$M = \frac{dT_{soil}}{dT} D(\rho_b C_s + P_w SMO - OC S_m C_w)$$

where G is soil heat flux at soil surface ($W m^{-2}$), F is soil heat flux at a depth of 8 cm ($W m^{-2}$), average of four REBS HFT3 soil heat flux sensors ($SHF_{1,2,3,4}$), dT_{soil} is change in soil temperature in upper 8-cm soil layer during time interval (K), average of two TVAR average soil temperature sensors (Campbell Scientific), T is time interval (1800 s), D is depth of layer above soil heat flux sensors (0.08 m), P_b and P_w are soil dry bulk density and density of water, respectively ($kg m^{-3}$), C_s and C_w are specific heats for soil solid portion and water, respectively ($Ukg^{-1} K^{-1}$), and $SMO_{0-0.08 m}$ is volumetric soil moisture content in the upper 8 cm soil layer ($m^3 m^{-3}$) measured with a CS615 soil moisture reflectometer (Campbell Scientific).

2.3. Eddy-covariance calculations

Based on the covariances of 20-Hz air temperature and specific humidity with vertical wind velocity, turbulent fluxes of H and LE ($W m^{-2}$) were estimated for 30-min averaging periods. EdiRe software (University of Edinburgh's eddy covariance system; see Moncrieff et al., 1997) was used to process the raw temperature, humidity, and three-dimensional wind time series to calculate fluxes (H_{EdiRe} and LE_{EdiRe}). Using the EdiRe package, temperature and humidity data were first passed through a digital recursive filter with a time constant of 400 s and a maximum period of 5 min. Axis rotation was performed to align the coordinate system with the mean streamline during each averaging period. Corrections were made for O_2 absorption by the krypton hygrometer, and for density effects (Webb et al., 1980). Occasionally it was not possible to calculate fluxes using EdiRe because the files containing the 20-Hz measurements were corrupted. However the CR5000 program provides a calculation of fluxes (H_{logger} and LE_{logger}), which we used when the EdiRe calculation were not available. The logger-estimated fluxes were reasonably close to EdiRe estimates for both Cerrado Denso (for LE , $r^2 = 0.935$, $SEE = 21.0 W m^{-2}$) and Campo Cerrado (for LE , $r^2 = 0.973$, $SEE = 13.1 W m^{-2}$). All flux estimates were filtered by first calculating the mean diurnal cycle for each month and then flagging values more than 2 standard deviations from the respective 30-min mean. Flagged values were examined visually along with other relevant data and field notes to identify and remove bad data points. Most discarded values were associated with wet sensor conditions resulting from rainfall.

Eddy-covariance estimates of scalar fluxes are known to be uncertain during periods of stable stratification with low turbulence, especially nighttime periods with low friction velocity (u_*) values, because of the possibility of significant amounts of horizontal trace gas advection during these periods (Alibin et al., 2000). In general, as Massman and Lee (2002) point out, turbulent scalar fluxes are proportional to the product of u_* and the vertical scalar gradient. In the case of CO_2 flux, however, the biological source strength is not influenced by turbulence (Wofsy et al., 1993; Goulden et al., 1996), and therefore should not

Table 1
Sensor vertical positions.

Sensor	sensor height/depth (m)	
	Station 51	Station 52
uvw , T_{sonic} , T_{fw} , q	14.21	4.77
R_{net}	13.43	4.09
K_d	13.48	4.04
K_u	13.38	3.94
THMPo RHHMP	13.94	4.66
WS, WD	14.04	4.71
RF	3.96	0.60
SHF(4)	-0.08	-0.08
T_{oll} (4)	-0.02 and -0.06	-0.02 and -0.06
SMo-o.oam	-0.04	-0.04

be dependent on u^* . Observed declines in CO_2 flux estimates with declines in u^* below a threshold lead many researchers (e.g. Gu et al., 2005) to replace eddy-covariance estimates of CO_2 flux with a temperature-dependent function for periods when u^* is below a site-specific threshold (Massman and Lee, 2002). While LE is probably also underestimated when u^* is low, the appropriate u' threshold to use for filtering cannot be determined from analysis of LE estimates alone, because of the high correlation between u' and LE across the full range of u^* values. In other words, because the source strength of water vapor is correlated with the degree of turbulent motion, LE generally decreases steadily as u^* declines, with no obvious break point.

The results reported here were not filtered for low values of u^* . However, we examined the sensitivity of nighttime LE estimates to u^* . As expected, we found that mean estimated nighttime LE declined with decreasing u^* at both field sites. For a five-month test period, mean nighttime LE from eddy-covariance measurements was 0.3, 3.3, 6.8, and 9.0 W m^{-2} for u^* ranges of 0–0.1, 0.1–0.2, 0.2–0.3, and 0.3–0.4, respectively, at the Cerrado Denso station, and 1.0, 4.3, 8.3, and 12.3 W m^{-2} , respectively, at the Campo Cerrado station. We tested the effect of removing nighttime LE values when u^* was below different thresholds, with no gap filling. Setting the u^* threshold at 0.1, 0.2, 0.3, and 0.4 resulted in increases in mean nighttime LE for the test period of 1.3, 3.7, 6.7, and 12.4 W m^{-2} , respectively, at the Cerrado Denso site, and 2.1, 5.7, 8.4, and 9.1 W m^{-2} , respectively, for the Campo Cerrado site. However, using a typical u' threshold of 0.2 m s^{-1} , would increase the overall (24 h) mean LE estimate by only about 3% and 5% for the two sites, respectively.

2.4. Energy balance approach

To estimate LE during periods when the eddy covariance equipment was at the other site or when direct LE measurements were missing for any reason, we employ an energy balance approach. The simplified energy balance of a vegetated surface can be written as:

$$R_{\text{net}} = G +] + H + LE \quad (2)$$

where R_{net} is net radiation, G is soil heat flux (Eq. (1)), $]$ is the change in heat storage within the vegetated layer, H is sensible heat flux to the atmosphere, and LE is the latent heat flux to the atmosphere (all terms expressed in W m^{-2}). Evapotranspiration (ET , $\text{kg m}^{-2} \text{s}^{-1}$) is equivalent to $\lambda^{-1} LE$, where λ is the latent heat of vaporization (kJ kg^{-1}). Written in the form of Eq. (2), all terms are normally positive during the day. R_{net} , G , and $]$ are positive downward, and H and LE positive upward. R_{net} and G were monitored continuously at both field sites throughout the study period. In the relatively short, sparse savanna vegetation, $]$ is small, and is ignored in this analysis. By independently estimating H (by eddy covariance or other means), LE can be obtained by rearranging Eq. (2).

2.5. Temperature variance-energy balance approach

When eddy-covariance estimates of both H and LE are unavailable, an alternative method of estimating H is needed in order to estimate LE using Eq. (2). The temperature variance-energy balance approach (TVEB), valid for rain-free, daytime (unstable) periods, utilizes the relationship between sensible heat flux and high-frequency variations in air temperature above the canopy (Tillman, 1972; De Bruin and Bink, 1994) to estimate Waterloo (1994) presents the TVEB method in the form:

$$HTVEB = h_{\sigma} \rho_a c_p \sqrt{(z_T - d) \frac{g}{T}} \cdot \sigma_T^2 \quad (3)$$

where h_{σ} is a constant set at 0.7 (Waterloo, 1994; based on Wijngaard and Coté, 1971), ρ_a is air density (kg m^{-3}), c_p is the specific heat of air at constant pressure ($\text{kJ kg}^{-1} \text{K}^{-1}$), z_T is the height of the air temperature sensor, g is gravitational acceleration (m s^{-2}), T is air temperature, σ_T is the standard deviation of air temperature calculated from 5-min blocks of temperature data sampled at 0.5 Hz, then averaged over each 3D-min interval, and the exponent a , set at 1.5 by Waterloo (1994), was selected in our study by optimizing H_{TVEB} with respect to eddy-covariance estimates of sensible heat flux (HEdiRe). A fine-wire thermocouple was maintained continuously at each site to provide observations of T and aT . Using H_{TVEB} and measured R_{net} and G , latent heat flux (LE_{TVEB}) can be estimated. The TVEB approach has been used with success by many other investigators (e.g. Vugts et al., 1993; De Bruin and Bink, 1994; Waterloo et al., 1999), and has been shown to yield evaporation estimates in close agreement with those obtained using well-established methods (Vugts et al., 1993; L.A. Bruijnzeel, personal communication, 1999).

2.6. LE estimates and energy closure

In all, five different methods were used to calculate latent energy flux: LE_{EdiRe} , direct eddy covariance measurements of LE with filtering and coordinate rotation done using EdiRe; LE_{logger} , direct eddy covariance measurements of LE with calculations done in logger; $LE_{\text{H_EdiRe}}$, energy balance residual using direct eddy covariance measurement of H with filtering and coordinate rotation done using EdiRe:

$$LE_{\text{H_EdiRe}} = R_{\text{net}} - G - HEdiRe \quad (4)$$

$LE_{\text{H_logger}}$, energy balance residual using direct eddy covariance measurement of H with calculations done by logger program:

$$LE_{\text{H_logger}} = R_{\text{net}} - G - H_{\text{logger}} \quad (5)$$

and LE_{TVEB} , energy balance residual using TVEB estimate of H :

$$LE_{\text{TVEB}} = R_{\text{net}} - G - HTVEB. \quad (6)$$

For the energy balance methods Eqs. (4)–(6), closure of the energy balance is forced. D , the energy closure ratio, $D = (H + LE) / (R_{\text{net}} - G)$ is always equal to unity because LE is calculated as a residual. For the direct eddy covariance measurements of LE , however, energy closure is not assured, and D is typically less than unity (Wilson et al., 2002). To make all the estimates comparable, we adjust the energy-balance-derived LE estimates to match the eddy-covariance measurements based on the mean value of D for each site. Eqs. (4)–(6) are modified to become:

$$LE_{\text{H_EdiRe}} = D(R_{\text{net}} - G) - HEdiRe \quad (7)$$

$$LE_{\text{H_logger}} = D(R_{\text{net}} - G) - H_{\text{logger}} \quad (8)$$

$$LE_{\text{TVEB}} = D(R_{\text{net}} - G) - HTVEB. \quad (9)$$

Energy closure error has numerous possible sources. Wilson et al. (2002) identify and discuss various suspected causes of error. This issue is discussed further in Sections 3.3 and 4.1.

The various estimates of LE are given above in order of preference, with LE_{EdiRe} considered the "best" or preferred method. To obtain the most complete LE record possible, we constructed a time series of the best available LE estimates (LE_{best}), taking the most preferred estimate available in each time interval.

2.7. Canopy conductance

Plant physiological controls on ET , through variations in stomatal conductance and leaf area, are represented in the Penman-

Monteith equation (Monteith, 1973) by the canopy conductance parameter (g_c). To examine variations in stomatal and leaf area controls, g_c was calculated by inverting the Penman-Monteith equation (see, for example, Lu et al., 2003).

3. Results

3.1. Climate and soil moisture

Daily climate and soil moisture time series during the study period are shown in Fig. 1. The highly seasonal precipitation regime is evident in the long-term mean monthly rainfall amounts (Fig. 1a). During periods when rainfall measurements were available at all sites, mean rainfall at the two tower sites differed by less than 2% and differed from the IBGE site by less than 6% (excluding outlier events). Note that the study period was relatively dry, with 2001, 2002, and 2003 each receiving about 80% of the long-term mean annual rainfall. The two wettest months of the study period were November 2002 (256 mm) and

January 2003 (274 mm), resulting in higher surface soil moisture in early 2003 than during the rest of the study period (Fig. 1b). Soil moisture was lowest in August 2001, with somewhat higher values during the 2002 dry season maintained by two small rain events, and relatively high values at the start of the 2003 dry season because of two significant late season rain events. Surface soil moisture at the Campo Cerrado site tended to increase more rapidly at the start of each wet season than at the Cerrado Denso site, presumably because of lower interception loss. During dry periods, surface soil moisture was depleted more rapidly at the more open Campo Cerrado site.

The annual cycle in sun angle is evident in the net radiation time series (Fig. 1c), with daily means reaching only about 125 W m^{-2} on clear days in June and exceeding 220 W m^{-2} in December. The influence of seasonal cloudiness is also seen as the day-to-day variability was much greater during each wet season. Daily net radiation values were generally very similar at the two sites.

Daily air temperature followed the net radiation cycle and was very similar at the two sites, which were both slightly cooler, on

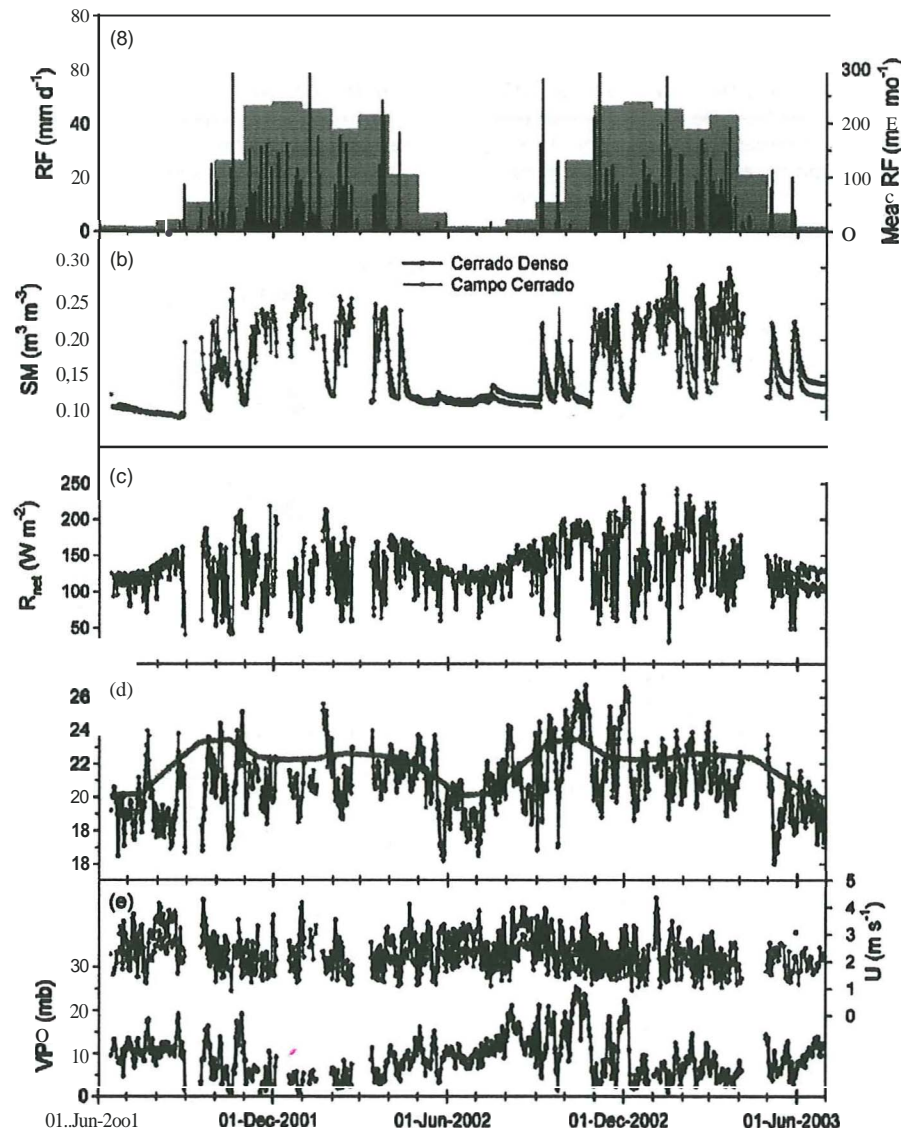


Fig. 1. Mean daily (a) rainfall, (b) surface (upper 8 cm) soil moisture, (c) net radiation, (d) air temperature, and (e) vapor pressure deficit (VPD) and wind speed (U) at Cerrado Denso and Campo Cerrado sites; and long-term mean monthly (a) rainfall (broad gray bars) and (d) temperature (thick gray line) based on 1980–2004 IBGE weather station data. Daily rainfall and long-term mean monthly rainfall and temperature obtained from the Reserva Ecológica do IBGE web site: <http://www.recor.org.br/cerrado/clima.html>.

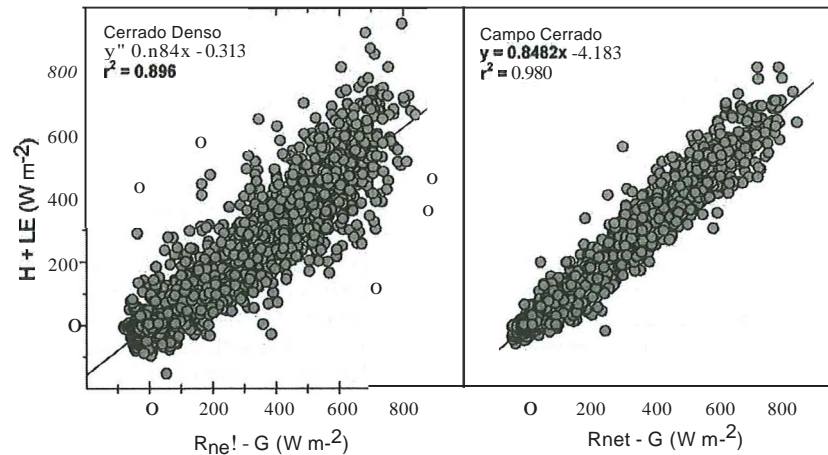


Fig. 2. Energy closure: 3D-min values of net radiation minus soil heat flux plotted against the sum of sensible and latent heat fluxes for Cerrado Denso and Campo Cerrado sites.

average, in relation to the IBGE long-term mean monthly values (Fig. 1d). Vapor pressure deficit (Fig. 1e) remained low (less than 6 mb in 2001 and 2002 and less than 10 mb in 2002 and 2003) during the height of the wet season (mid-December through mid-January), then increased from February through early October, reaching as high as 25 mb. Wind speed (U) had an annual cycle with a maximum of around $3\text{--}4\text{ m s}^{-1}$ in August and a minimum of around $2\text{--}2.5\text{ m s}^{-1}$ during February–April.

3.2. LAI

Variation in LAI was coupled to seasonal variation in moisture availability, with LAI reaching peak values at both sites during the wet season (results not shown). Significant differences in maximum LAI were seen between the two study years. Total LAI reached 3.45 at the Cerrado Denso site and 2.01 at the Campo Cerrado site in December 2001; whereas the peak LAI during the second study year was only 2.62 (February 2003) and 2.15 (April 2003), respectively, for the two sites. As expected, ground layer LAI was usually higher at the Campo Cerrado site while shrub and tree layer LAI was consistently higher at the Cerrado Denso site.

3.3. Energy balance closure

The energy closure ratio (D) can be estimated as the slope of the regression of $H + LE$ on $R_{\text{net}} - G$, or calculated from the mean values of H , LE , R_{net} , and G . As previously mentioned, eddy-covariance-based turbulent exchange estimates typically underestimate measured available energy. In the energy balance closure plots (Fig. 2), the slope of the least squares regression line indicated mean energy closure ratios (D) of 0.7784 and 0.8482 for the Cerrado Denso and Campo Cerrado sites, respectively, while the corresponding values of D based on the means of H , LE , R_{net} , and G were 0.7762 and 0.8206 (data not shown).

3.4. Footprint analysis

Using June–October 2001 data for the two sites, the footprints of each tower were evaluated using the method of Kormann and Meixner (2001, Eq. (2)) and compared with the fetch distances. Based on field surveys, relatively homogeneous Cerrado Denso vegetation extended approximately 700 m in the direction of the most frequent daytime winds ($90\text{--}115^\circ$). At the Campo Cerrado site, homogeneous vegetation extended about 300 m in the direction from which daytime winds commonly occur. Fig. 3

shows the mean diurnal cycle of the proportion of the estimated footprint falling within the fetch area of each tower, i.e. 700 and 300 m for Cerrado Denso and Campo Cerrado, respectively. Greater than 97% of daytime fluxes and around 94% of nighttime fluxes originated from within the areas of homogeneous vegetation upwind of each tower.

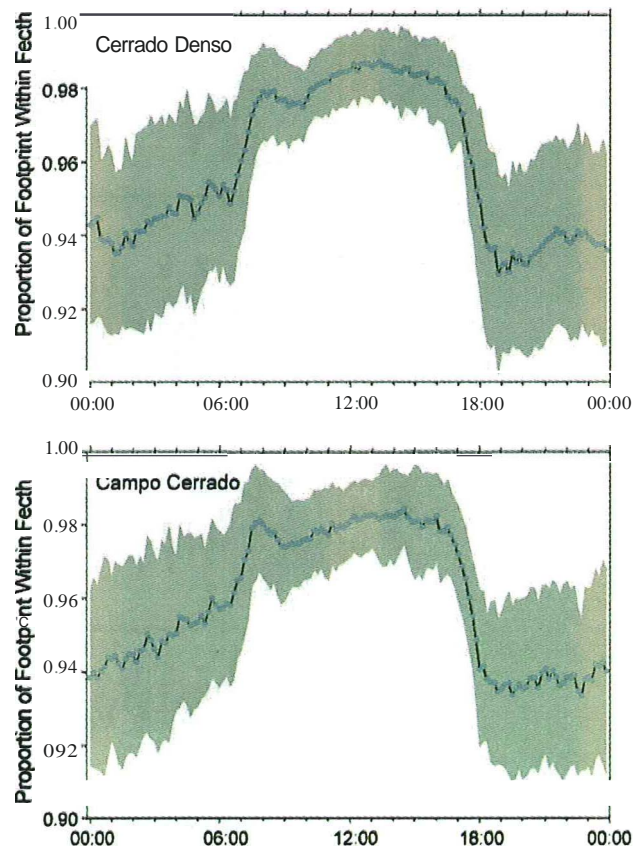


Fig. 3. Footprint analysis based on Kormann and Meixner (2001) for Cerrado Denso (top panel) and campo Cerrado (bottom panel) sites. The proportion of footprint within the fetch is estimated as the cumulative Integrated flux from the area within 700 m upwind of the Cerrado Denso tower and 300 m upwind of the campo Cerrado tower; plus or minus 1 standard deviation shown by gray shading.

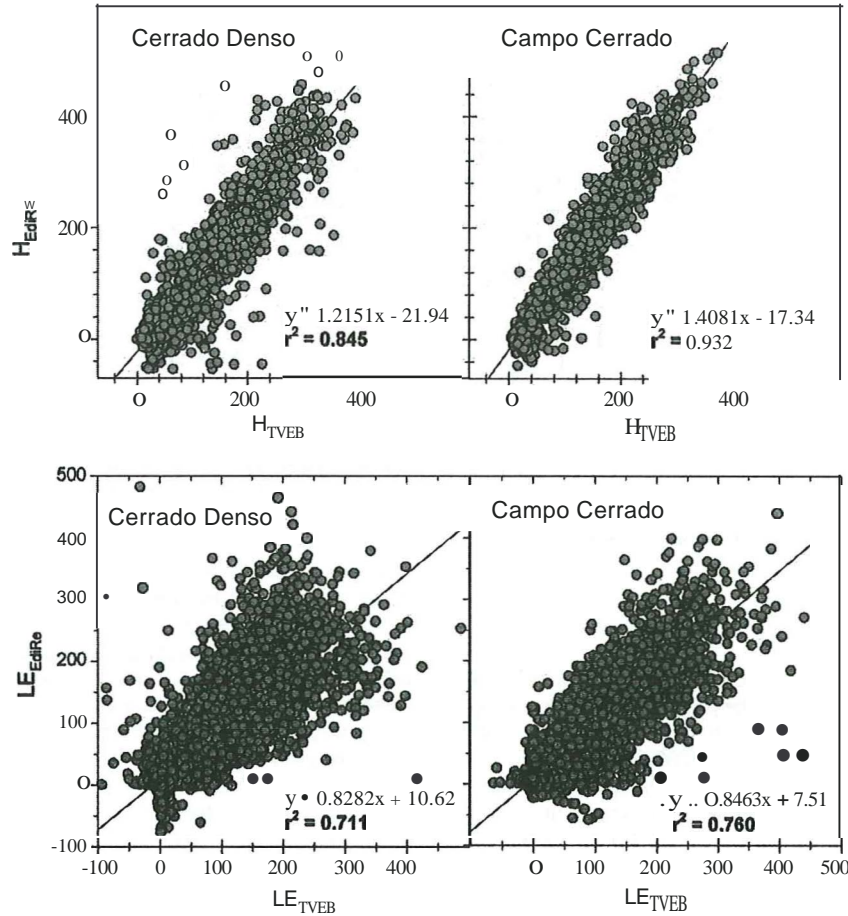


Fig. 4. Daytime, 30-min estimates of sensible heat flux derived from Eq. (4) (H_{TVEB}) versus eddy-covariance estimates (H_{EdIRE}) (top panels) and latent heat flux derived from Eq. (7) (LE_{TVEB}) versus eddy-covariance estimates (LE_{EdIRE}) (bottom panels) for Cerrado Denso (left panels) and Campo Cerrado (right panels) sites.

3.5. TVEB testing and calibration

Estimated daytime, 30-min values of sensible heat flux derived from Eq. (3) (H_{TVEB}) were compared with concurrent eddy-covariance estimates of H . We found that a value of 2.5 for the coefficient, a , in Eq. (3) produced the best fit of a linear regression (Fig. 4, top panels). The resulting regression equation for each site was then used to adjust estimates of H_{TVEB} used in Eq. (9). For nighttime values, the mean nighttime H/R_{net} ratio for each site (0.5462 for Cerrado Denso and 0.3776 for Campo Cerrado) was used. Values of LE_{TVEB} compare reasonably well with LE_{EdIRE} at both Cerrado Denso ($r^2 = 0.698$, $SEE = 47.2 \text{ W m}^{-2}$) and Campo Cerrado ($r^2 = 0.798$, $SEE = 39.2 \text{ W m}^{-2}$) sites (Fig. 4, bottom panels).

3.6. Mean diurnal patterns

Figs. 5 and 6 show the mean diurnal patterns of R_{net} , LE , and g_c at each site, for each month of the record. Again, R_{net} was quite similar for the two sites, however, daytime values were slightly higher for Cerrado Denso than Campo Cerrado around midday in some months (Fig. 5, upper two panels). Mean diurnal LE patterns (Fig. 5, lower two panels) show that midday ET was clearly higher at the Cerrado Denso sites in nearly all months. Canopy conductance (g_c) was consistently higher during the morning and often dropped sharply by early afternoon at both sites (Fig. 6). During some months (e.g. October 2001 and 2002), g_c reached a minimum in the early afternoon before increasing slightly later in the afternoon.

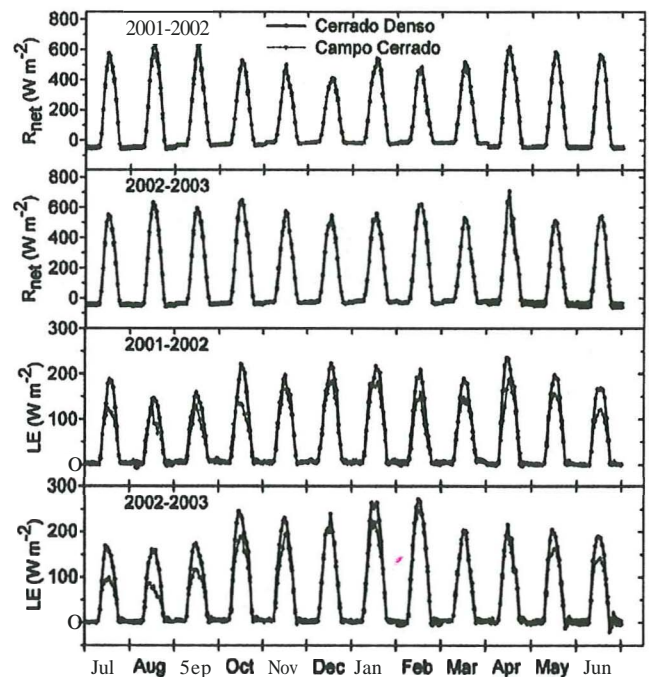


Fig. 5. Mean diurnal cycle of net radiation (upper two panels) and latent energy flux (lower two panels) for each month at Cerrado Denso (51 land) and Campo Cerrado (52) sites.

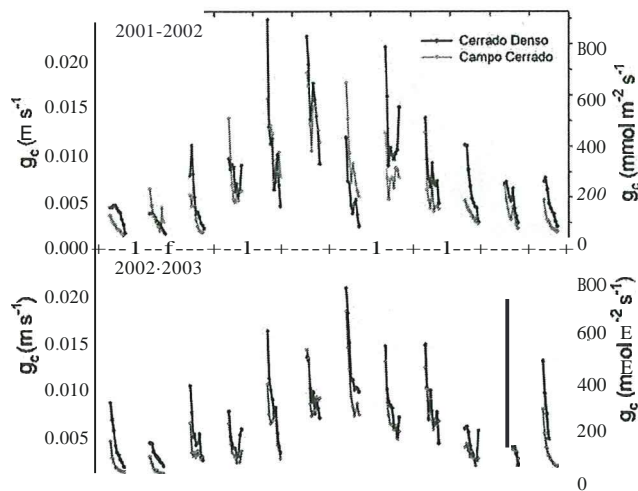


Fig. 6. Mean daytime patterns of canopy conductance for each month at Cerrado Denso and Campo Cerrado sites.

3.7. Daily flux time series

A distinct annual cycle can be seen in the daily LE time series for both sites with a maximum during the peak of the wet season and a minimum near the end of the dry season (Fig. 7, top panel). Higher values were reached during the 2002-2003 wet season than the previous year, but with greater variability. High day-to-day variability throughout the record is explained in part by fluctuations in R_{net} due to cloudiness (see Fig. 1c). LE was consistently higher for Cerrado Denso than Campo Cerrado, especially during the dry season.

The daily Bowen ratio ($fJ = H/LE$) time series also shows a clear annual cycle with a peak at the end of the dry season and a minimum around January (Fig. 7, bottom panel). Values for the two sites were similar at the height of the wet season, but diverged sharply, with higher values for the Campo Cerrado site throughout the dry season, especially during 2002.

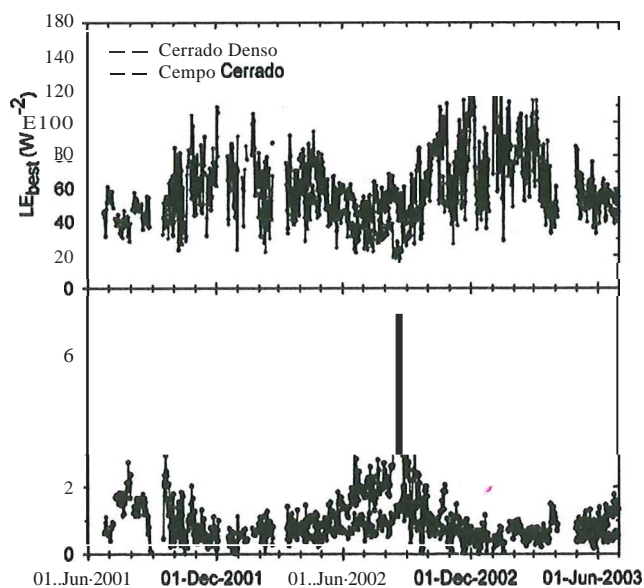


Fig. 7. Daily LE based on best available estimate for each 30-min interval (upper panel) and daily Bowen ratio (H/LE) (lower panel) at Cerrado Denso and Campo Cerrado sites.

3.8. Energy balance

Monthly energy balance at each site is summarized in Table 2. As seen at the daily interval, LE for Cerrado Denso was generally similar to or greater than for Campo Cerrado, with the highest difference between the sites occurring during the dry season. Exceptions occurred in December 2002 and March 2003, when LE was slightly greater at the Campo Cerrado site. LE (ET) averaged 63.9 ± 11.7 and $53.5 \pm 14.3 \text{ W m}^{-2}$ (2.25 ± 0.41 and $1.91 \pm 0.50 \text{ mm d}^{-1}$) at Cerrado Denso and Campo Cerrado, respectively.

4. Discussion

4.1. ET, energy balance and closure

Monthly mean ET at the Cerrado Denso site was in the range $1.7\text{--}2.5 \text{ mm d}^{-1}$ during the dry season and $2.2\text{--}3.2 \text{ mm d}^{-1}$ during the wet season (Table 2). For Campo Cerrado, the ranges were $1.1\text{--}2.0 \text{ mm d}^{-1}$, dry season, to $1.5\text{--}2.9 \text{ mm d}^{-1}$, wet season. At a nearby site within the IBGE, characterized by Campo Sujo vegetation, Santos et al. (2003) found ET to vary between a dry season low of approximately 1.1 mm d^{-1} during July 1999 and $2.9\text{--}3.7 \text{ mm d}^{-1}$ during the 1998 and 1999 wet seasons. Mean annual ET of 823 and 689 mm yr^{-1} at the Cerrado Denso and Campo Cerrado sites, respectively, are similar to annual ET estimates for other tropical savanna sites. For example, prior ET estimates include 958 mm yr^{-1} for Eucalypt open-forest savanna in northern Australia (Hutley et al., 2000), and 538 , 771 , and 732 mm yr^{-1} for herbaceous savanna, tree savanna, and woodland savanna, respectively, in the Orinoco lowlands (San José et al., 2008).

As expected, ET observations at our tropical savanna sites were significantly lower and showed more pronounced seasonal variation than those measured in forests in the Amazon region, such as the tropical wet forest at Santarem, Pará, where ET ranges from 3.18 ± 0.67 to $3.96 \pm 0.65 \text{ mm d}^{-1}$ (da Rocha et al., 2004). Unlike our sites, where ET reached a maximum during the wet season, ET at Santarem was highest during the dry season presumably because the deep rooting habit of the predominant arboreal vegetation prevented drought stress during the dry season when net radiation was highest (da Rocha et al., 2004). Cerrado vegetation has a grass layer that becomes inactive during the dry season. Moreover, although many cerrado trees have access to underground water reserves, they maintain similar rates of daily water loss throughout the year because of hydraulic constraints (Meinzer et al., 1999; Goldstein et al., 2008).

At both of our sites, the annual course of ET is not fully explained by variation in net radiation, which was limited by cloudiness during the wet season, and hence had only a weak annual cycle. The reduction in dry season ET at the two sites suggests that the effects of lower moisture availability were limiting the process, through the combined effects of reductions in soil evaporation, stomatal conductance, and LAI. The annual course of the Bowen ratio strongly suggests that reduced water availability constrained dry season ET at both sites (Fig. 7, bottom panel). Similarly, Miranda et al. (1996) found that latent heat flux, which reached a maximum during the wet season, was reduced to about half that level in September at a cerrado site 50 km NE of Brasilia.

The mean energy closure of 0.7784 and 0.8482 for the Cerrado Denso and the Campo Cerrado sites, respectively, (all within the range found at FLUXNET sites ($0.34\text{--}1.69$, with a mean of 0.835 , Wilson et al., 2002), and especially for similar ecosystems; for example, closure for four different eddy-covariance measurement systems was found to range from 0.71 to 0.91 over grassland in OK, USA (Twine et al., 2000)). Possible explanations for energy balance discrepancies include differences in instrument footprints for

Table 2
Monthly energy balance summary for Cerrado Denso (CD) and Campo Cerrado (CC) sites. IBGE Reserve, Brazil.

	R_{net} ($W m^{-2}$)		G ($W m^{-2}$)		H ($W m^{-2}$)		LE ($W m^{-2}$)		Closure error ^a ($W m^{-2}$)		Closure ratio ^a (%)		IT (mmd^{-1})		LE/R _{net} ratio	
	CD	CC	CD	CC	CD	CC	CD	CC	CD	CC	CD	CC	CD	CC	CD	CC
july 01	115	112	-0.9	0.6	39.8	66.2	54.0	38.1	21.9	6.8	81.0%	93.9%	1.91	1.34	0.47	0.34
August 01	139	130	0.0	0.8	61.2	71.9	47.0	37.0	30.6	20.1	78.0%	84.4%	1.66	1.30	0.34	0.28
September 01	140	130	0.1	-0.3	58.0	70.6	53.1	40.6	29.0	19.1	79.3%	85.4%	1.87	1.43	0.38	0.31
October 01	127	126	-0.7	-0.3	43.7	54.1	66.7	50.1	17.1	22.0	86.6%	82.6%	2.35	1.77	0.53	0.40
November 01	124	123	-0.4	-0.6	33.3	38.6	64.2	59.0	26.7	26.2	78.5%	78.8%	2.26	2.08	0.52	0.48
December 01	118	114	-1.0	-0.9	18.9	29.5	73.9	64.8	26.2	20.6	78.0%	82.1%	2.61	2.29	0.63	0.57
january 02	153	144	0.2	-0.3	51.0	24.7	74.6	65.4	27.1	54.6	82.3%	62.2%	2.63	2.31	0.49	0.45
february 02	123	117	-1.5	-1.4	35.7	36.7	63.8	43.8	24.8	37.7	80.0%	68.1%	2.25	1.54	0.52	0.37
March 02	134	122	-0.6	-1.1	37.4	41.3	60.9	52.7	36.0	29.2	73.2%	76.3%	2.15	1.86	0.46	0.43
April 02	143	145	-1.5	-2.0	36.4	52.1	71.2	55.7	37.2	39.2	74.3%	73.3%	2.51	1.96	0.50	0.38
May 02	124	124	-2.4	-1.9	37.8	55.2	56.8	48.0	31.4	22.7	75.1%	82.0%	2.00	1.69	0.46	0.39
june 02	117	118	-2.2	-1.6	41.4	62.9	52.0	37.6	26.2	18.7	78.1%	84.3%	1.83	1.32	0.44	0.32
july 02	114	113	-0.9	-0.5	39.6	63.2	49.2	32.3	26.2	17.7	77.2%	84.4%	1.74	1.14	0.43	0.29
August 02	143	139	-0.2	0.3	61.1	89.5	52.4	29.7	29.5	19.7	79.4%	85.8%	1.85	1.05	0.37	0.21
September 02	144	143	-0.2	-0.5	55.3	77.8	57.7	42.4	30.9	23.1	78.5%	83.9%	2.03	1.50	0.40	0.30
october 02	166	167	0.7	0.4	52.7	75.9	82.3	66.0	30.5	24.9	81.5%	85.1%	2.90	2.33	0.50	0.39
November 02	149	146	-0.4	-0.4	40.4	48.3	75.6	63.2	33.7	34.9	77.5%	76.2%	2.67	2.23	0.51	0.43
December 02	143	141	-0.9	-0.7	31.5	44.2	71.8	75.3	40.4	22.5	71.9%	84.2%	2.53	2.65	0.50	0.53
january 03	153	152	-0.5	-0.6	30.8	46.1	89.6	74.2	32.8	32.0	78.6%	79.0%	3.16	2.62	0.59	0.49
february 03	170	171	-0.9	-0.9	46.8	55.7	84.7	82.8	39.1	33.5	77.1%	80.5%	2.99	2.92	0.50	0.48
March 03	130	133	-1.4	-1.5	36.6	41.3	61.3	66.0	33.6	27.3	74.4%	79.7%	2.16	2.33	0.47	0.50
April 03	149	149	-0.6	-1.0	43.6	48.8	58.5	56.8	47.2	44.6	68.4%	70.3%	2.06	2.00	0.39	0.38
May 03	106	118	-2.8	-2.3	27.5	45.0	57.8	54.2	24.0	21.4	78.0%	82.3%	2.04	1.91	0.54	0.46
june 03	106	128	-3.0	-2.4	29.7	57.9	55.1	49.5	24.6	23.3	77.5%	82.2%	1.94	1.75	0.52	0.39
Mean	135	134	-0.9	-0.8	41.2	54.1	63.9	53.5	30.3	26.7	77.7%	80.3%	2.25	1.91	0.48	0.40
Std. Dev.	18	16	0.9	0.9	10.9	16.0	11.7	14.3	6.6	10.1	3.7%	6.7%	0.41	0.50	0.07	0.09

Note: R_{net} - net radiation. G - soil heat flux. H - sensible heat flux. LE - latent heat flux. ET - evapotranspiration.

^a Closure error and closure ratio presented here are affected by assumed energy closure ratio used in energy balance estimates for some periods (see Eqs. (7)-(9)).

available and turbulent energy fluxes, errors in net radiation and soil heat flux measurements, failure to include changes in energy storage within biomass and canopy air space, and loss of low and high frequency turbulent flux contributions (da Rocha et al., 2004; Wilson et al., 2002). Footprint differences certainly contribute to random error, but would not be expected to produce consistent underestimates across the range of sites and instrument configurations reported in the literature. Daytime averages of the sum of biomass and canopy air space storage were found to be less than $10W m^{-2}$ in old-growth tropical forest in eastern Amazonia (da Rocha et al., 2004) and would be expected to be lower in shorter, lower biomass savanna vegetation. Further, these energy storage fluxes would average close to zero over the diurnal cycle, and therefore, would not contribute much to energy closure error. Twine et al. (2000) recommended assuming that LE and H are the sources of closure error, but that the Bowen ratio is correctly estimated. This assumption allows the surface energy balance to be closed by the "Bowen-ratio closure" method, i.e. by dividing LE and H by the mean value of D. Adopting this method would imply that the true values of LE and H in our study are higher by a factor of D^{-1} (1.288 for Cerrado Denso and 1.219 for Campo Cerrado).

4.2. Effects of variation in soil moisture and LAI

Annual fluctuations in the Bowen ratio at each site (Fig. 7, bottom panel) were in phase with variation in both soil moisture and LAI. To examine these influences on evapotranspiration more closely, variations in the Bowen ratio were plotted as a function of soil moisture and LAI (Fig. 8). The Bowen ratio at both sites increased as surface-layer soil moisture decreased (Fig. 8, top), but with a stronger dependency at the Campo Cerrado site (exponential decay coefficients significantly different at $p = 0.10$). At the daily time scale (not shown), sharp increases in the daily Bowen ratio (decreases in the relative amount of energy devoted to ET) were seen at both sites, but especially at the Campo Cerrado site, as

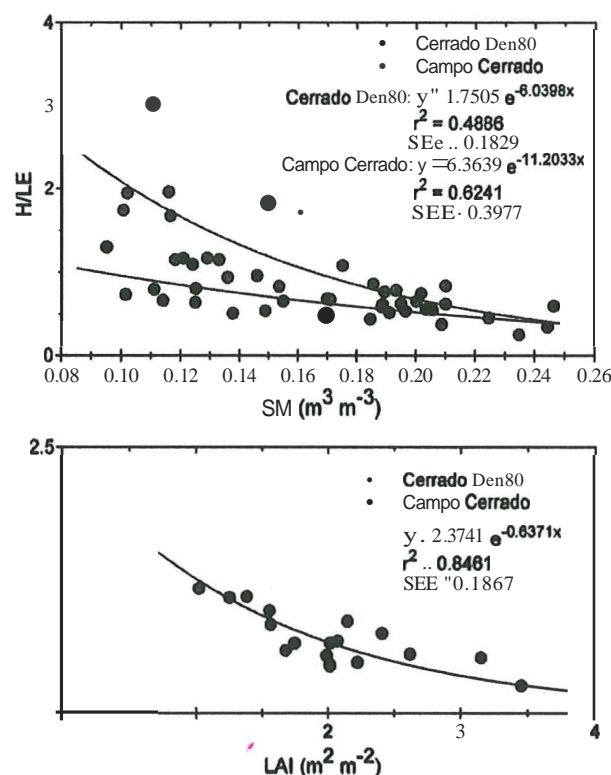


Fig. 8. Influences on Bowen ratio: monthly Bowen ratio as a function of soil moisture at the two sites (top panel); and monthly Bowen ratio as a function of LAI at the two sites (bottom panel). The exponential decay coefficients for the two curves in the top panel are significantly different at $p = 0.10$. The relationship between H/LE and LAI was not significantly different for the two sites, therefore the curve shown in the bottom panel is fitted to data from both sites.

surface soil moisture fell below about 0.125 m m^{-3} . The greater sensitivity of the Bowen ratio to surface soil moisture variation at the Campo Cerrado site was likely due to the dominance of shallow-rooted herbaceous plants and the larger contribution of soil evaporation there as compared with the Cerrado Denso site. Energy partitioning at the two sites converges at the high end of the soil moisture range, as can be clearly seen in Fig. 8 (top). Monthly Bowen ratio values for both sites decreased in similar fashion as LAI increased (Fig. 8, bottom). Meinzer et al. (1999) found only small seasonal differences in tree transpiration per unit leaf area in the IBGE Ecological Reserve, suggesting that plant response to water stress there is mainly in the form of LAI changes. Our findings indicate that surface soil moisture directly affected ET more strongly at the Campo Cerrado site, especially when the soil was extremely dry, whereas ET was approximately equally sensitive to leaf area changes at the two sites. The data shown in Fig. 8 (bottom) suggest that LAI variation explains both seasonal and spatial ET regulation across the woody plant density gradient in Cerrado.

4.3. Difference in ET and energy balance between Campo Cerrado and Cerrado Denso

The relative difference in monthly LE between the two sites tended to be lower in the wet season (generally less than 40% higher at Cerrado Denso) than in the dry season (Table 2). The difference was especially small (<20%) during December 2002 and February–May 2003. These months were also notable for having the smallest relative difference in total LAI between the two sites. Fig. 9 shows the apparent influences of soil moisture (top panel, decay coefficient significant at $p = 0.01$) and LAI (bottom panel, decay coefficient significant at $p = 0.002$) on the observed ratio of LE between the two sites. The upper panel of Fig. 9 shows that LE at the two sites was generally more similar when surface layer soil moisture was high at the Campo Cerrado site. The lower panel suggests that the observed differences in LE between the two sites can be partly explained by differences in LAI. The ratio of LE among these two sites approached one as LAI at the two sites became similar. The relative difference in LE increased to about 29% when the ratio of LAI at Cerrado Denso to that at Campo Cerrado reached 2, after which greater relative LAI differences had less influence on the difference in LE. Because of the high correlation between soil water status and leaf area, especially during the dry season (Hoffmann et al., 2005), it is not possible to say conclusively whether variation in the relative difference in LE between the two sites was controlled more strongly by soil moisture or LAI.

4.4. Diurnal ET cycle

Stomatal control of ET was evident in the daytime variation in canopy conductance (Fig. 6). Based on seasonally averaged daytime values (not shown), g_e was consistently higher throughout the day for the Cerrado Denso site than the Campo Cerrado site during both wet (October–March) and dry (April–September) seasons, in agreement with the higher LAI there. Conductance was significantly lower for both sites in the dry season, also attributable to changes in LAI as was similarly shown for tree transpiration in the study area by Bucci et al. (2008). In both seasons and for both sites, mean g_e declined throughout the daytime period. While site-to-site and season-to-season differences can be partly explained by LAI differences, this decline was the result of increasing stomatal resistance as water stress and vapor pressure deficit (VPD) steadily increased, and perhaps also the result of daytime desiccation of the soil surface, particularly at the Campo Cerrado site. In each season, the effects of water stress, VPD, and/or soil desiccation on the ET pattern were approximately the same for the two sites. To further

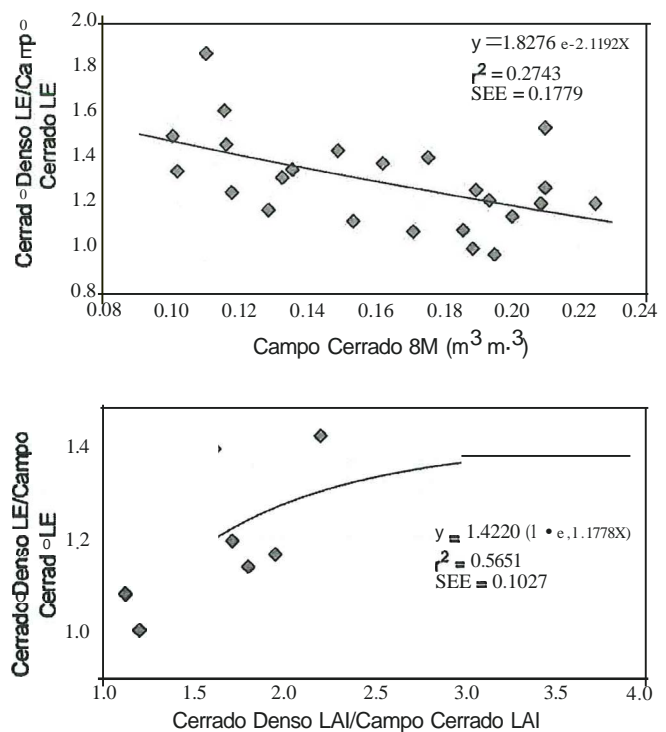


Fig. 9. Influences on the relative difference in LE at the two sites: the ratio of LE at Cerrado Denso to LE at Campo Cerrado as a function of monthly soil moisture at Campo Cerrado (top panel); and the ratio of LE at Cerrado Denso to LE at Campo Cerrado as a function of the ratio of LAI at Cerrado Denso to LAI at Campo Cerrado (bottom panel).

examine this issue, canopy resistance (r_c) is plotted as a function of VPD in Fig. 10 for each site and for wet and dry seasons. During both seasons, r_c increases with increasing VPD, but more strongly at the Campo Cerrado site (slopes of best-fit linear functions, not shown, are significantly different at $p = 0.005$ and $p = 0.0005$ for wet and dry seasons, respectively). This is consistent with the findings of Bucci et al. (2008), who showed that r_c of sites with higher tree density and higher tree LAI was less sensitive to VPD changes. Based on the curves shown in Fig. 10, at a VPD of 10 mb, r_c is 26% and 40% higher on average at the Campo Cerrado site than the Cerrado Denso site during the wet and dry seasons, respectively, and 18% and 32% higher on average during the dry season than the wet season at the Cerrado Denso and Campo Cerrado sites, respectively.

Bucci et al. (2004) found that nighttime sap flow in trees in the study area amounted to 13–28% of daily sap flow. They attribute this finding to a combination of recharge of stem water storage and nocturnal transpiration. As seen in Fig. 5 (lower two panels), stand level ET at both sites is very small at night, based on the tower measurements. The apparent lack of agreement regarding nighttime ET may point to a greater contribution of stem tissue rehydration in the previously observed nighttime sapflow. It should be noted that very low nighttime transpiration rates were measured for the herbaceous layer (S.J. Bucci, unpublished data, 2008), which may help to explain the low stand level values found here. On the other hand, this finding may be related to uncertainty in the nighttime stand level estimates, associated with periods of weak turbulence as indicated by low values of u^* . As previously discussed, because of the difficulty in selecting an appropriate u^* threshold, the results presented here were not subjected to a u^* filter. However, we note that for a typical u^* threshold of 0.2 m s^{-1} , mean nighttime LE would increase to about 15% and 18% of total LE

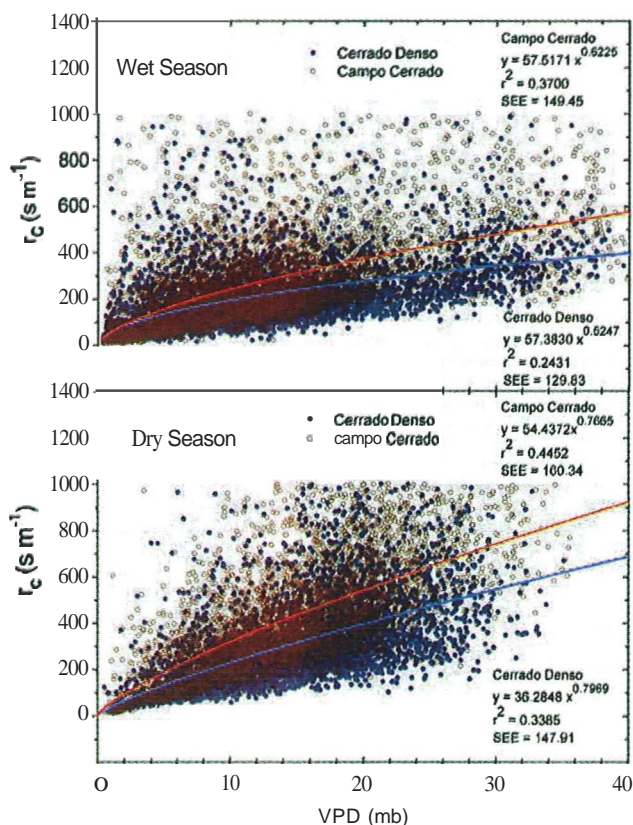


Fig. 10. Canopy resistance ($r_c = \text{g}^{-1}$) as a function of vapor pressure deficit (VPD) at Cerrado Denso and Campo Cerrado sites for wet season (top panel) and dry season (bottom panel). Only periods with $0 < r_c < 1000 \text{ s m}^{-1}$ included in analysis.

for the Cerrado Denso and Campo Cerrado sites, respectively, within the range found by Bucci et al. (2004).

4.5. Use Δ /temperature variance method as a low-cost alternative to eddy covariance

Eddy covariance methods require expensive sensors and present numerous difficulties involving equipment maintenance and data storage and analysis. The TVEB approach was found to produce reliable estimates of sensible and latent heat fluxes at the two study sites and might be considered a reasonable alternative to the eddy covariance approach. However, the results presented here were conditioned on estimates derived from our eddy-covariance measurements, without which, uncertainty in the TVEB estimates would have been much greater. Therefore, the method is not recommended as an alternative for sites where contemporaneous eddy covariance observations are not available, at least for a representative test period. For situations in which a single eddy covariance system is available and can be relocated to several sites in a network, as was done here for two sites, the TVEB method can provide reliable daytime LE estimates after optimization with respect to the eddy-covariance estimates.

5. Conclusions

The findings presented here provide insights into the spatial variability of ET and surface energy balance within a cerrado landscape. Significant differences were found in ET rates between Cerrado Denso and Campo Cerrado vegetation, presumably due to differences in woody plant density, root depth and density, and leaf area. This implies that analogous differences exist among the other

types of cerrado vegetation, e.g. we would expect to find even lower ET rates for a cover type such as Campo Sujo, which has a lower woody plant density than Campo Cerrado. The fact that ET at the two sites converge as LAI becomes similar suggests that leaf area is the dominant control on spatial and temporal variations in the proportion of energy used for ET. While stomatal control is evident in diurnal ET patterns, the effects are similar across sites and seasons. Thus, predictions of regional ET values for the Cerrado landscape have to take into account variations in tree density and LAI and hence the proportion of different Cerrado physiognomies. Anthropogenic perturbations and global climate change are expected to alter the balance between herbaceous and woody components of tropical savannas. The results of this study can enhance the robustness model predictions of spatial and temporal changes in savanna hydrological cycles.

Acknowledgements

This work was supported by grants from the National Science Foundation (USA) grant #0296174 and grant #0322051 and CNPq Brazil. We thank the Reserva Ecologica do IBGE for logistic support.

References

- Aubinet, M., Grelle, A., Ibrom, A., Rannik, O., Moncrieff, J., Foken, T., Kowalski, A.S., Martin, P.H., Bernhoffer, P., Bernhofer, Ch., Clement, R., Elbers, J., Granier, A., Grunwald, T., Morgenstern, K., Pilegaard, K., Rebmann, e., Snijders, W., Valentini, R., Vesala, T., 2000. Estimates of the annual net carbon and water exchange of European forests: the EUROFLUX methodology. *Advances in Ecological Research* 30, 114–175.
- Bucci, S.J., Scholz, F.G., Goldstein, G., Meinzer, F.e., Hinojosa, J.A., Hoffmann, W.A., Franco, A.C., 2004. Processes preventing nocturnal equilibrium between leaf and soil water potential in tropical savanna woody species. *Tree Physiology* 24, 1119–1127.
- Bucci, S.J., Scholz, F.G., Goldstein, G., Hoffmann, W.A., Meinzer, F.C., Franco, A.C., Giambelluca, T., Miralles-Wilhelm, F., 2008. Controls on stand transpiration and soil water utilization along a tree density gradient in a Neotropical Savanna. *Agricultural and Forest Meteorology* 148, 839–849. doi: 10.1016/j.agrormet.2007.1.1013.
- da Rocha, H.R., Goulden, M.L., Miller, S.D., Menton, M.e., Pinto, L.D.V.O., de Freitas, H.e., e Silva Figueira, A.M., 2004. Seasonality of water and heat fluxes over a tropical forest in eastern Amazonia. *Ecological Applications* 14, 522–532.
- De Bruin, H.A.R., Bink, N.J., 1994. The use of Δ as a temperature scale in the atmospheric surface layer. *Boundary Layer Meteorology* 70, 79–93.
- Eamus, D., Hutley, L.B., O'Grady, A.P., 2001. Daily and seasonal patterns of carbon and water fluxes above a north Australian savanna. *Tree Physiology* 21, 977–988.
- FAO, 1993. *Production Yearbook*. Food and Agriculture Organization, United Nations, Rome, Italy.
- Goldstein, G., Meinzer, F.e., Bucci, S.J., Scholz, F.G., Franco, A.C., Hoffmann, W.A., 2008. Water economy of neotropical savanna trees: six paradigms revisited. *Tree Physiology* 28, 395–404.
- Goulden, M.L., Munger, J.W., Fan, S.-M., Daube, B.e., Wofsy, S.C., 1996. Measurements of carbon sequestration by long-term eddy covariance: methods and a critical evaluation of accuracy. *Global Change Biology* 2, 169–182.
- Gu, t., Falge, E.M., Boden, T., Baldocchi, D.D., Black, T.A., Saleska, S.R., Suni, T., Verma, S.B., Vesala, T., Wofsy, S.e., Xu, L., 2005. Objective threshold determination for nighttime eddy flux filtering. *Agricultural and Forest Meteorology* 128, 179–197. doi: 10.1016/j.agrormet.2004.11.00G.
- Hoffmann, W.A., da Silva Jr., E.R., Machado, G.C., Succi, S.J., Scholz, F.G., Goldstein, G., Meinzer, F.C., 2005. Seasonal leaf dynamics across a tree density gradient in a Brazilian savanna. *Oecologia* 145, 307–316.
- Hutley, L.B., O'Grady, A.P., Eamus, D., 2000. Evapotranspiration from Eucalypt open-forest savanna of Northern Australia. *Functional Ecology* 14, 183–194.
- Hutley, L.B., O'Grady, A.P., Eamus, D., 2001. Monsoonal influences on evapotranspiration of savanna vegetation of northern Australia. *Oecologia* 126, 434–443.
- Kormann, R., Meixner, F.x., 2001. An analytical footprint model for non-neutral stratification. *Boundary-Layer Meteorology* 99, 207–224.
- tu, P., Yunusa, I.A.M., Walker, R.R., Milller, W.J., 2003. Regulation of canopy conductance and transpiration and their modelling in irrigated grapevines. *Functional Plant Biology* 20, 689–698.
- Massman, W.J., Lee, X., 2002. Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges. *Agricultural and Forest Meteorology* 119, 121–144.
- Meinzer, F.C., Goldstein, G., Franco, A.C., Bustamante, M., Iglar, E., Jackson, p., Caldas, L., Rutdel, P.W., 1999. Atmospheric and hydraulic limitations on transpiration in Brazilian Cerrado woody species. *Functional Ecology* 13, 273–282.

- Meinzer, F.e., Brooks, J.R., Bucci, S.J., Goldstein, G., Scholz, F.G., Warren, J.M., 2004. Converging patterns of uptake and hydraulic redistribution of soil water in contrasting woody vegetation types. *Tree Physiology* 24, 919-928.
- Miranda, A.e., Miranda, H.S., Lloyd, J., Grace, J., McIntyre, J.A., Meir, P., Riggan, P., Lockwood, R., Brass, J., 1997. Carbon dioxide fluxes over a Cerrado *sensu stricto* in central Brazil. In: Gash, J.H.C., Nobre, e.A., Roberts, J.M., Victoria, R.L. (Eds.), *Amazonian Deforestation and Climate*. John Wiley and Sons, Chichester, UK, pp. 353-363.
- Miranda, A.C., Miranda, H.S., Lloyd, J., Grace, J., Francey, R.J., McIntyre, J.A., Meir, P., Riggan, P., Lockwood, R., Brass, J., 1997. Fluxes of carbon, water and energy over Brazilian cerrado: an analysis using eddy covariance and stable isotopes. *Plant, Cell and Environment* 20, 315-328.
- Moncrieff, J.B., Massheder, J.M., de Bruin, H., Elbers, J., Friborg, T., Heusinkveld, B., Kabat, P., Scott, S., Sogaard, H., Verhoef, A., 1997. A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide. *Journal of Hydrology* 188-189, 589-611.
- Monteith, J.L., 1973. *Principles of Environmental Physics*. Elsevier, New York.
- Moreira, M.Z., Scholz, F.G., Bucci, S.J., Sternberg, L.S., Goldstein, G., Meinzer, F.e., Franco, A.e., 2003. Hydraulic lift in a neotropical savanna. *Functional Ecology* 17, 573-581.
- Oliveira, R.S., Bezerra, L., Davidson, E.A., Pinto, F., Klink, e.A., Nepstad, D.e., Moreira, A., 2005. Deep root function in the soil water dynamics in cerrado savannas of central Brazil. *Functional Ecology* 19, 574-581.
- Santos, A.B., Silva, G.T.D.A., Miranda, H.S., Miranda, A.C., Lloyd, J., 2003. Effects of fire on surface carbon, energy and water vapour fluxes over campo sugo savanna in central Brazil. *Functional Ecology* 17, 711-719.
- San José, J., Montes, R., Grace, J., Nikonova, N., Osio, A., 2008. Land-use changes alter radiative energy and water vapor fluxes of a tall-grass *Andropogon* field and a savanna-woodland continuum in the Orinoco lowlands. *Tree Physiology* 28, 425-435.
- Scholes, R.J., Archer, S.R., 1997. Tree-grass interactions in savannas. *Annual Review of Ecology and Systematics* 28, 517-544.
- Scholz, F.G., Bucci, S.J., Goldstein, G., Meinzer, F.C., Franco, A.C., 2002. Hydraulic redistribution of soil water by neotropical savanna trees. *Tree Physiology* 22, 603-612.
- Scholz, F.G., Bucci, S.J., Goldstein, G., Moreira, M.Z., Meinzer, F.e., Domec, J.-e., Villalobos Vega, R., Franco, A.e., Miralles-Wilhelm, F., 2008. Biophysical and life history determinants of hydraulic lift in Neotropical savanna trees. *Functional Ecology*, doi:10.1111/j.1365-2435.2008.01452.x.
- Tillman, J.E., 1972. The indirect determination of stability, heat and momentum fluxes in the atmospheric boundary layer from simple scalar variables during dry unstable conditions. *Journal of Applied Meteorology* 11, 783-792.
- Twine, T., Kustas, W., Norman, J., Cook, D., Houser, P., Meyers, T., Prueger, J., Starks, P., Wesely, M.L., 2000. Correcting eddy-covariance flux underestimates over a grassland. *Agricultural and Forest Meteorology* 103, 279-300.
- Vufts, H.F., Waterloo, M.J., Beekman, F.J., Frumau, K.F.A., Bruijnzeel, L.A., 1993. The temperature variance method: a powerful tool in the estimation of actual evaporation rates. In: *Hydrology of Warm Humid Regions (Proceedings of the Yokohama Symposium, July 1993)*, IAHS Publication No. 216, pp. 251-260.
- Waterloo, M.J., 1994. Water and nutrient dynamics of *Pinus caribaea* plantation forests on former grassland soils in southwest Viti Levu, Fiji. Ph.D. Thesis. Vrije University, Amsterdam, Netherlands, 478 pp.
- Waterloo, M.J., Bruijnzeel, L.A., Vufts, H.F., 1999. Evaporation from *Pinus caribaea* plantations on former grassland soils under maritime conditions. *Water Resources Research* 35, 2133-2144.
- Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. *Quarterly Journal of the Royal Meteorological Society* 106, 85-100.
- Wijngaard, J.e., Coté, O.R., 1971. The budgets of turbulent kinetic energy and temperature variance in the atmospheric surface layer. *Journal of the Atmospheric Sciences* 28, 190-201.
- Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Bernhofer, P., Bernhofer, e., Ceulemans, R., Dolman, H., Field, e., Ibrom, A.G.A., Law, B.E., Kowalski, A., Meyers, T., Moncrieff, J., Monson, R., Oechel, W., Tenhunen, J., Valentini, R., Verma, S., 2002. Energy balance closure at FLUXNET sites. *Agricultural and Forest Meteorology* 113, 223-243.
- Wofsy, S.C., Goulden, M.L., Munger, J.W., Fan, S.M., Bakwin, P.S., Daube, B.e., Bassow, S.L., Bazzaz, F.A., 1993. Net exchange of CO₂ in a midlatitude forest. *Science* 260, 1314-1317.