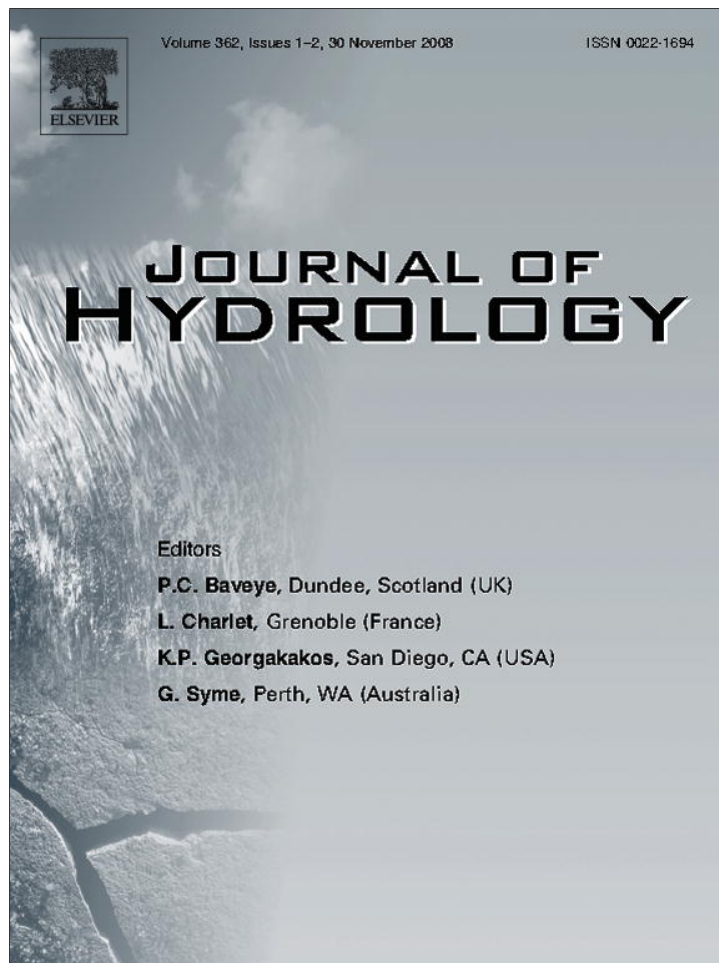


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Analysis of energy fluxes and vegetation-atmosphere parameters in irrigated and natural ecosystems of semi-arid Brazil

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Natural vegetation

Summary Knowledge on evapotranspiration is essential in quantifying water use depletion and to allocate scarce water resources to competing uses. Despite that an extensive literature describes the theoretical mechanisms of turbulent water vapour transport above and within crop canopies fewer studies have examined land surface parameters within composite landscapes of irrigated crops and semi-arid natural vegetation. Aiming to improve parameterizations of the radiation and energy balance in irrigated crops and natural vegetation, micro-climatic measurements were carried out on irrigated land (vineyards and mango orchard) and natural vegetation (caatinga) in the semi-arid zone of the São Francisco River basin (Brazil) from 2002 to 2005. The fractions of 24 h incident solar radiation available for net radiation were 46%, 55%, 51% and 53%, for wine grape, table grape, mango orchard and caatinga, respectively. Daily evaporative fractions of the net available energy used as latent heat flux (λE) were 0.80, 0.88, 0.75 and 0.33 respectively. The daylight values of bulk surface resistances (r_s) averaged 128 s m^{-1} , 73 s m^{-1} , 133 s m^{-1} and 1940 s m^{-1} for wine grape, table grape, mango orchard and caatinga,

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respectively. Simplified parameterizations on roughness and evaporation resistances were performed. It could be concluded that net radiation can be estimated by means of a linear expression with incident global solar radiation depending on the type of vegetation. The variability of aerodynamic resistance (r_a) could be mainly explained by the friction velocity (u_*) which on turn depends on the surface roughness length for momentum transport (z_{0m}). The experimental data showed that for sparse canopies z_{0m} being 9% of the mean vegetation height is a doable operational rule for the semi-arid region of São Francisco River basin. The seasonal values of r_s for irrigated crops were highly correlated with water vapour pressure deficit. The availability of analytical methods to assess r_a and r_s makes the one-step Penman–Monteith equation suitable for the computation of actual evapotranspiration and water productivity analyses.

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Introduction

The São Francisco River traverses six Brazilian states, comprising a total area of 640,000 km². From this total, roughly 340,000 ha are irrigated, representing about 10% of the total São Francisco basin arable land. Fifty two percent of the basin area is located in the semi-arid zone in north-eastern Brazil, which is characterized by four-month rainy season (from January to April) with a rainfall ranging from 350 to 800 mm y⁻¹. The region produces high quality fruits like grapes and mangoes. Water managers in this semi-arid zone are faced with several challenges, such as increasing water resources scarcity, competition among different water user groups, over-exploitation of aquifers, climate and land use changes, non-source pollution, erosion, and sedimentation. Water policy makers have to work out strategies for integrated water management, which rely on a proper knowledge of the physical conditions of the river basins.

The basin water depletion is caused mainly by actual evapotranspiration (ET_a) from a range of crops and natural vegetation types, soil, build-up areas and water bodies. A proper knowledge of ET_a for various land covers is essential for managing scarce water resources and for keeping long-term evapotranspiration in balance with precipitation. Experimentally, ET_a can be determined by using weighing lysimeters, eddy covariance technique and the Bowen Ratio energy balance method. The use of lysimeters for trees is often not recommended, due to the development of the root systems. ET_a in irrigated crops and natural vegetation can be determined by analyzing the available energy at the land surfaces, the relevant potential differences (gradients of air temperature or air specific humidity), and the aerodynamic and bulk surface resistances (e.g. Gash and Shuttleworth, 2007). Examples of energy balance measurements by means of the Bowen ratio method above vegetated surfaces can be found in for instance Heilman et al. (1994, 1996). Eddy correlation technique is considered to be a standard procedure for determining the latent heat flux (λE) in field conditions (e.g. Oliver and Sene, 1992; Lund and Soegaard, 2003), albeit this method is not free from errors.

The commonly used Penman–Monteith equation is an appropriate mathematical framework to compute ET_a at local and regional scales (e.g. Dolman, 1992; Riddersma and De Ridder, 1996; Bastiaansen and Bandara, 2001). Despite that an extensive literature describes the theoretical mecha-

nisms of turbulent transport above and within crop canopies; fewer studies have examined the actual soil-vegetation-atmosphere-transfer parameters within landscapes of irrigated crops being interchanged with semi-arid natural land cover. Some earlier examples of evapotranspiration research in composite arid zone landscape are provided by for instance Kustas et al. (1994) for Walnut Gulch in Arizona, Chehbouni et al. (2001) for Mexico and Kite and Droogers (2000) for Turkey.

The objectives of the research described in this paper are (i) to review and improve parameterizations of the radiation and energy balances in irrigated crops and natural vegetation using field measurements, (ii) to predict 24 h net radiation and latent heat flux from instantaneous values and (iii) to determine the evaporation resistances – r_a and r_s – from irrigated crops (vineyards and mango orchard) and natural vegetation (caatinga).

Vegetation types investigated

Wine grape

The wine grape investigated was from Vitivinícola Santa Maria farm near the town of Lagoa Grande (Lat. 09°02' S; Long. 40°11' W), in Pernambuco state. The cultivar was *Petite Syrah*, 11 years old at the start of the experiments in 2002. The plants were spaced at 1.20 m × 3.50 m, trained vertically to a bilateral cordon and spur pruned. The cordon wire was at a height of 1.6 m with no foliage wires (a sprawl type canopy developed). There was no cover crop between the rows, and they were oriented in a north–south direction. The shoots were allowed to grow freely over the wires.

The daily drip irrigated area of 4.13 ha was bordered on all sides by other wine grapes. There was one drip emitter between two plants in the rows at a discharge rate of 4 L h⁻¹, suspended on the wire. Although it is common in many wine production areas not to irrigate vines at bud-break, or shortly thereafter, the irrigation started soon after pruning without quantifying the water demand. The soil is sandy with a water retention capacity that increases with depth, presenting a cracked rock layer below 60 cm evidenced at the time of installation of the tensiometers.

The study involved two growing seasons during this year. The duration of the first growing season (GS1) was 132 days, elapsing from 7 February to 19 June 2002, while the second growing season (GS2) comprised 136 days, from 08 July to 22

November 2002. Grapes were picked to produce wine from both periods.

Table grape

The table grape plot was located in the Vale das Uvas farm near the town of Petrolina (Lat. 09°18' S; Long. 40°22' W), Pernambuco state. The cultivar was *Superior Seedless* and the vineyard was only 2 years old during the first growing season. The plants were spaced at 3.5 m × 4.0 m, with the rows also oriented in the north–south direction. The vineyard had an overhead horizontal trellis system at 1.80 m height. The cover crop consisted of a mixture of legumes and grasses, and was incorporated into the soil after budbreak.

The plot investigated was 5.13 ha, surrounded by other table grapes. The grapes were daily micro sprinkler irrigated, with one in-line micro sprinkler between two vines on the ground at a discharge rate of 44 L h⁻¹ which wetted 70% of the soil surface. As in wine grape, the farmer started the irrigation soon after pruning with large amount of water, thereby promoting high rates of direct soil water evaporation and cover crop transpiration at initial stages. The soil is also sandy throughout the vertical profile, but its water retention capacity does not increase with depth. Water holding capacity is higher in the upper soil layer (0–20 cm) due to high organic matter content.

The measurements involved two growing seasons (GS1 and GS2), during the same period but in different years: both from 08 July to 07 October, in 2002 and in 2003, because the crop was left resting between the two growing seasons, to avoid possible direct damage in fruits and high incidence of fungi diseases due to rainfall. The plants were not girdled nor sprayed with gibberellic acid and the leaves were not removed from fruit zone. At the stage of vegetative growth, non-fruitful shoots and lateral shoots growing in the fruiting zone were removed and at fruit growth stage the berries were protected with a white cover from direct solar radiation.

Mango orchard

The experiments with mango orchard were carried out from 2003 to 2005 in Fruitfort farm, Petrolina (Lat. 09°22' S, Long. 40°34' W), Pernambuco state, Brazil. The cultivar was *Tommy Atkins*, 18 years old (in 2003), spaced in a regular square pattern at 10 m × 10 m, with an average height of 5.5 m, mean leaf area index (LAI) of 5.6 and daily micro sprinkler irrigated in an area of 11.92 ha, with one in-line micro sprinkler between two trees on the ground at a discharge rate of 44 L h⁻¹ wetting 70% of the soil surface. The irrigation requirements were calculated based on reference evapotranspiration and crop coefficients adjusted by crop stage. The orchard was bordered on all sides by other mango crops which similar height. There was no cover crop in the sandy soil which has low water retention capacity.

Mango is a perennial crop. The study comprised two growing seasons. The duration of the first period was 390 days, from 01 October 2003 to 24 October 2004. The measurements continued into a second period of 370 days, elapsing from 25 November 2004 to 29 November 2005. For the two growing seasons, the growth cycle extended from November

to October. The fruit trees undergo vegetative growth between November and January, followed by branch development from January to May. The mango trees flowered from May to July, with fruit initiation between June and July. Fruit growth occurred in July to August. Fruit maturation was during August and September. The fruits were picked in the period between September and October. The trees required some pruning during the crop development.

Natural vegetation

Caatinga is a vegetation type which location is mainly the Brazilian northeast. The flux tower was installed at 09°03' S and 40°19' W, near the town of Lagoa Grande, Pernambuco state. The data comprised two years of measurements (2004 and 2005). This natural vegetation is a mixture of species and the more frequent are *Caesalpinia microphylla* Mart., *Manihot pseudoglaziovii* Pax et. K Hoffman, *Croton conduplicatus* Kunth and *Sapium lanceolatum*. The mean height of the mixed species in the site was 8 m. Caatinga is defined by bush aspects possessing small leaves or thorns. These are some of the solutions found by the plants to avoid the loss of water by the epidermis. Besides some species have a loss of leaves in the dry season and some species store water. The vegetation is distributed in an irregular way, inhabiting contrasting areas similar to forests, with soil patches of bare soil and clumps of vegetation interspersed.

Data collection

The Bowen ratio surface energy balance method was used to measure the partition of net available energy into sensible and latent heat fluxes in vineyards. The sensors were installed at the centre of the plots. The gradients of air temperature and vapour pressure above the crops were calculated by using wet and dry thermocouples of copper/constantan at 0.5 and 1.5 m above the canopies.

In wine grape, the surface albedo ($\alpha_0 = R_R/R_G$) was measured through incident (R_G) and reflected (R_R) global solar radiation acquired with pyranometers faced up and down (model Eppley, number 19579, Rhode Island, USA). The net radiation (R_n) was measured at 1 m over the canopy with two net radiometers (model NR-Lite, Kipp & Zonnen, Delft, the Netherlands), each one installed above a row of plants. The soil heat flux (G) was obtained with four heat flux plates (HFT3-L, REBS, Radiation and Energy Balance Systems, Seattle, WA and Hukseflux, Delft, the Netherlands) at 2 cm soil depth and 0.5 m from the plants. G was not corrected for the heat storage above the plates; however as the surface above 2 cm is very thin, it was assumed that these corrections could be neglected. Wind speed was measured with anemometers (R.M., Young wind Sentry, 03101, Michigan, USA) at two levels, i.e. 1.0 and 2.0 m above the canopy. Air temperature and relative humidity at 0.5 m near the leaves were obtained with a probe from Vaisala (model HMP 35A, Helsinki, Finland) at the same height of the first thermocouple. Soil moisture (θ) profiles were weekly monitored with tensiometers located between the drip emitters and the vine trunks in two rows. The sampling depths were 20, 40 and 60 cm considered to represent the effective root zone for vineyards in local soil and cultural conditions.

The same method, measurement procedures and equipment's manufacturers as for wine grapes were set up for table grapes with few differences. Only one net radiometer was installed above a row of plants. Two soil heat flux plates (model HFT3-L, REBS, Radiation and Energy Balance Systems, Seattle, WA) were used. As for table grapes, it was also assumed that corrections for G due to the heat storage above the plates could be neglected. Air temperature and relative humidity near the leaves was measured by a probe (SKH 2013, Sky instruments LTD, Llandrindod Wells, UK) 0.5 m below the trellis system and only one anemometer was installed at 1.0 m above the canopy. θ profiles were also weekly monitored with tensiometers located between the micro sprinklers and the vine trunks along two rows at same soil depths as for wine grapes.

During the experiments in mango orchard, the eddy covariance (EC) method was applied. The system, installed at the centre of the plot, determined the sensible (H) and latent heat fluxes (λE) by a three-axis sonic anemometer (Model CSAT3, Campbell Scientific, Logan, UT) and a krypton hygrometer (Model KH20, Campbell Scientific, Logan, UT), respectively, connected to a datalogger (Model CR10X, Campbell Scientific, Logan, UT, USA). The sensors were set at 3 m above the crown of a mango tree with a sampling frequency of 16 Hz. The net radiation (R_n) was acquired with one net radiometer (model NR-Lite, Kipp & Zonnen, Delft, The Netherlands) above a row of plants at a height of 2.5 m above the canopy. At this same height the surface albedo was measured with pyranometers faced up and down (model Eppley, number 19579, Rhode Island, USA). The soil heat flux (G) was acquired with two heat flux plates (model HFT3-L, REBS, Radiation and Energy Balance Systems, Seattle, WA) at 2 cm soil depth and below the projected tree crown at 1 m from the trunk. As for vineyards, it was also assumed that corrections for G due to the heat storage above the plates could be neglected. Air temperature and relative humidity near the leaves was measured with a probe (SKH 2013, Sky instruments LTD, Llandrindod Wells, UK) installed at the same height of the radiation sensors. θ profiles were weekly monitored with tensiometers located between the micro sprinklers and the mango trees. The sampling depths were 20, 40, 60, 80, 100 and 120 cm considered to represent the effective root zone for mango orchards in local soil and cultural conditions.

All low frequency automatic measurements in irrigated crops were taken at each 5 s interval and averages of 10 min were stored in a datalogger of the same manufacturer as for the eddy covariance system in mango orchard.

The EC system over caatinga was installed at 11 m height above the ground, and consisted of a sonic anemometer from the same manufacturer as in mango orchard and a gas analyser (LI7500, LI-COR, Lincoln, Nebraska, USA) with the same sampling frequency and datalogger as for mango orchard. All components of short and long wave solar radiation were measured with pyranometers and pyrgeometers facing up and down (Kipp & Zonnen, Delft, The Netherlands) at a height of 10 m from the ground. R_n was acquired at the same height of the other radiation sensors and G was measured with one flux plate at 2 cm soil depth. As for irrigated crops, it was also assumed that corrections for G due to the heat storage above the plates could be neglected. Both, the net radiometer and the flux plate were from the same man-

ufacturer as in mango orchard. Microclimatic measurements of air temperature and relative humidity were taken above the vegetation with a probe from Vaisala (model HMP 45C-L, Helsinki, Finland) at the same height of the radiation sensors. The low frequency data in caatinga were collected each minute and 10 min averages were stored in the datalogger (CR23X, Campbell Scientific, Logan, UT, USA).

Theory

The overall calculations of radiation and energy balances are described in many text books. First the components of net radiation will be discussed, as R_n is the main supplier of energy required to drive the evapotranspiration process. The longwave radiation received from the atmosphere ($R_{L\downarrow}$) can be computed from the Stephan Boltzmann equation for all cases with direct measurements of air temperature (T_a), provided that the apparent emissivity of the atmosphere (ε_a) is known. Various empirical solutions exist to describe ε_a (Brunt, 1939; Swinbank, 1963). During a comparative study executed by the University of Idaho (Allen et al., 2000), the empirical equation developed by Bastiaanssen (1995) appeared to perform most favourably, provided that it is calibrated against local observations (see also Allen et al., 2007). Thus:

$$\varepsilon_a = a(-\ln \tau_{sw})^b \quad (1)$$

where τ_{sw} is the shortwave atmospheric transmissivity and a and b are regression coefficients.

All radiation components of the caatinga site were measured, which made it feasible to isolate ε_a from measured $R_{L\downarrow}$ and T_a values. The a and b coefficients of Eq. (1) could be calibrated and this equation was applied to retrieve ε_a and $R_{L\downarrow}$ in the irrigated sites. The incoming longwave radiation ($R_{L\downarrow}$) could be computed from the Stephan Boltzmann equation for all irrigated crops, after making the proper correction for atmospheric emissivity:

$$R_{L\downarrow} = \varepsilon_a \sigma T_a^4 \quad (2)$$

where σ ($5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$) is the Stefan–Boltzmann constant and T_a (K) the air temperature.

Values of surface albedo (α_0) were obtained by measuring from incoming global solar radiation R_G and outgoing solar radiation R_R in wine grape, mango orchard and caatinga. For table grape R_R was estimated from the regression equation between net short wave radiation ($R_G - R_R$) and R_n developed by Azevedo et al. (1997) for the same crop in semi-arid conditions of São Francisco River basin.

Using the 24 h values of short wave components ($R_G - R_R$), R_n and $R_{L\downarrow}$ the 24 h values of $R_{L\downarrow}$ could be estimated as a residual in radiation balance for irrigated fruit crops where this radiation parameter was not measured.

The 24 h values of the net radiation (R_{n24}) can be described by the 24 h values of shortwave component, with a correction term for net longwave radiation at the same time scale. De Bruin (1987) and de Bruin and Stricker (2000) reported on the use of the following equation:

$$R_{n24} = (1 - \alpha_{024})R_{G24} - a\tau_{sw24} \quad (3)$$

where a is a regression coefficient of relationship between net long wave radiation (R_{n24}) and atmospheric transmissivity (τ_{sw24}) at daily scale.

Eq. (3) has the advantage that the emissivities during daytime and night time necessary for solving the Stephan Boltzmann equation can be omitted. Thus, R_{n24} can be quantified if net shortwave radiation is measured and the adjusting factor, a , is known.

The Penman–Monteith equation was developed to predict evapotranspiration from vegetated surfaces (Allen et al., 1998):

$$\lambda E = \frac{\Delta(R_n - G_0) + \rho_a c_p D / r_a}{\Delta + \gamma(1 + r_s / r_a)} \quad (4)$$

where Δ (kPa °C⁻¹) is the slope of the saturated vapour pressure curve, ρ_a (kg m⁻³) is the air density, c_p (J kg⁻¹ K⁻¹) is the air specific heat at constant pressure, D (kPa) is the vapour pressure deficit and γ (kPa °C⁻¹) is the psychrometric constant.

The evaporative fraction describes the complex energy partitioning process by single parameters:

$$E_f = \lambda E / (R_n - G) \quad (5)$$

The advantage is the simplicity and that E_f describes whether soils are dry or wet. Very wet vegetated soils tend to E_f becoming 1.0 and very dry soils to E_f being approximately zero.

The drag force between land and atmosphere in the Penman–Monteith equation is accounted for the aerodynamic resistance (r_a), and this parameter requires the surface roughness conditions z_{oh} and friction velocities u_* to be specified:

$$r_a = \frac{\ln \left[\frac{z-d}{z_{oh}} \right]}{ku_*} - \psi_h \left(\frac{z-d}{L} \right) \quad (6)$$

where z_{oh} (m) is the roughness length governing transfer of heat and vapour away from the land surface into the atmosphere, k is the von Karman's constant (0.41), u_* (m s⁻¹) is the friction velocity, z (m) is the measurement height, d (m) is the displacement height, ψ_h is the stability correction due to buoyancy and L is the Obukhov length. In vineyards L was obtained by an iterative numerical method starting with a value of 10⁶ m, while for mango orchard and natural vegetation it was derived from eddy covariance measurements.

For vineyards the friction velocity was calculated using flux profile relationships (u_{FP*}) with two-level near-ground wind speed measurements:

$$u_{FP*} = \frac{k(u_2 - u_1)}{\ln \left[\frac{z_2-d}{z_1-d} \right] - \psi_m \left(\frac{z_2-d}{L} \right) + \psi_m \left(\frac{z_1-d}{L} \right)} \quad (7)$$

where u_1 and u_2 are the wind speed values at heights z_1 and z_2 (2.6 m and 3.6 m for wine grape and 2.8 m and 3.8 m for table grape).

In the case of table grape, the wind speed measurements u_2 at z_2 (3.8 m) were absent; only air temperature (T_a) was measured at this height. The wind speed values for this level were estimated by means of the H calculations, the vertical air temperature increments ΔT between z_1 and z_2 and the r_a values. Initially, a neutral condition in the logarithm wind profile equation was used to derive the first value of u_* , which could be subsequently improved with L .

The eddy covariance data of mango orchard and caatinga could be used to acquire the friction velocity (u_{EC*}) directly without wind speed measurements at multiple heights:

$$u_{EC*} = \sqrt{-\overline{w'u'}} \quad (8)$$

where u' and w' are instantaneous departures from the average horizontal (u) and vertical (w) wind speed measured by the sonic anemometers. The roughness length for moment transfer was obtained from either u_{FP*} or u_{EC*} as

$$z_{0m} = \frac{z-d}{\exp \left(\frac{ku(z)}{u_{FP,EC*}} + \Psi_m \left(\frac{z-d}{L} \right) \right)} \quad (9)$$

where $u(z)$ is the wind speed at the first level ($z = z_1$) in vineyards or at the height of the sonic anemometer in mango orchard or caatinga.

Ratios of d/h_v were usually reported to lie in the range of 0.6 (Garrat, 1978), although several authors assumed (Hicks, 1973) or calculated (Riou et al., 1987) a negligible d for extensive vineyards. We considered $d = 0.66 h_v$ (Allen et al., 1998) and solve z_{0m} as the unknown in Eq. (9). Early measurements in closed canopies reported $z_{0m} = 0.13 h_v$, (e.g. Monteith, 1973). The roughness parameters for vegetation under incomplete canopy cover were less and the z_{0m}/h_v relationship seems to vary more than for closed canopies (e.g. Hicks, 1973; Garrat, 1978; Riou et al. 1987). Garrat (1978) found z_{0m}/h_v of 0.05 for a natural savannah; Driese and Reiners (1997) reported averaged z_{0m}/h_v values of 0.04, 0.04 and 0.13 for natural sagebrush, saltbush and greasewood, respectively. Van Dijk et al. (2004) found a value of $z_{0m}/h_v = 0.03$ for a rain fed cropping system with maize and cassava. Originally the relationship between z_{oh} and z_{0m} was denoted by the dimensionless quantity kB^{-1} :

$$kB^{-1} = \ln(z_{0m}/z_{oh}) \quad (10)$$

In many hydro-meteorological models containing a sub-model for the vegetation-atmosphere interaction, the results of Thom (1972) and Garrat and Hicks (1973) are used and kB^{-1} for vegetation is taken as a constant at about 2.0. Following them and also the standard work of Allen et al. (1998), we assume a kB^{-1} value of 2.3, being equivalent to $z_{oh} = 0.1z_{0m}$.

The surface resistance parameters in the Penman–Monteith equation are combined into one parameter, the 'bulk' surface resistance (r_s) which operates in series with the aerodynamic resistance (r_a). Microclimatic data of air temperature and relative humidity were used together R_n , λE and G to estimate r_s inverting Eq. (4). The effects of D and θ in the r_s values of irrigated fruit crops and natural vegetation growing in semi-arid conditions of São Francisco River basin were evaluated and specific relationships were found.

Results and discussion

Energy fluxes and their parameterizations

Radiation balance

The daily values of the radiation balances are presented in Table 1. R_n averaged 46% of R_G for wine grape, 55% for table grape, 51% for mango orchard, and 53% for caatinga. The rule of thumb of R_n being approximately 50% of R_G (e.g.

Table 1 Daily averages of the radiation balance for irrigated crops (Wine Grape – WG, Table Grape – TG, Mango orchard – MG) for the first (GS1) and second (GS2) growing seasons and for natural vegetation (Caatinga – CT) for two years (2004 and 2005): global solar radiation (R_G), reflected solar radiation (R_R), incident longwave radiation ($R_{L\downarrow}$), emitted longwave radiation ($R_{L\uparrow}$), and ratio of reflected solar radiation (R_R/R_G) and net radiation (R_n/R_G) to global solar radiation

Vegetation/period	R_G ($\text{MJ m}^{-2} \text{d}^{-1}$)	R_R ($\text{MJ m}^{-2} \text{d}^{-1}$)	$R_{L\downarrow}$ ($\text{MJ m}^{-2} \text{d}^{-1}$)	$R_{L\uparrow}$ ($\text{MJ m}^{-2} \text{d}^{-1}$)	R_R/R_G (-)	R_n/R_G (-)
WG_GS1	20.10	4.20	34.56	40.69	0.21	0.48
WG_GS2	23.87	5.15	32.95	41.36	0.22	0.43
TG_GS1	20.96	3.85	32.37	37.88	0.18	0.55
TG_GS2	20.49	3.83	32.57	38.27	0.19	0.54
MG_GS1	21.19	3.29	34.09	41.42	0.16	0.50
MG_GS2	21.92	3.30	33.97	41.50	0.15	0.51
CT_2004	21.60	3.08	33.51	40.47	0.14	0.54
CT_2005	20.84	2.70	34.16	41.52	0.13	0.52

Makkink, 1957; Oliver and Sene, 1992) was herewith confirmed to be a realistic first estimate.

For all sites, there was a consistent relationship between the half hourly values of R_n and R_G (Fig. 1). The slopes of all equations ranged between 0.60 and 0.75, and were similar to those obtained by Oliver and Sene (1992) for a rainfed vineyard in Spain, as well as for mature Sultana grapes, growing in a T-trellis system (Yunusa et al., 2004) and other ecosystems in Australia (Hughes et al., 2001). The high correlations imply that R_n can be estimated from R_G only. This is relevant because net radiometers are only occasionally available; sometimes there are technical problems associ-

ated with the sensors during some periods of an experiment. The spatial variation of R_G across vast river basins can nowadays be well described from satellites by means of cloud cover data, which aids the description of the spatial variation of R_n .

The relationship between R_G and R_n is, to a large extent, affected by the surface albedo (α_0). The seasonal behaviour of α_0 is shown in Fig. 2 for all vegetation types studied. The oscillation in daily averaged values is mainly due to the crop stages, cultural practices and irrigation for irrigated crops and rainfall regime in natural vegetation. The cover crop in table grape caused high α_0 values before bud break. After

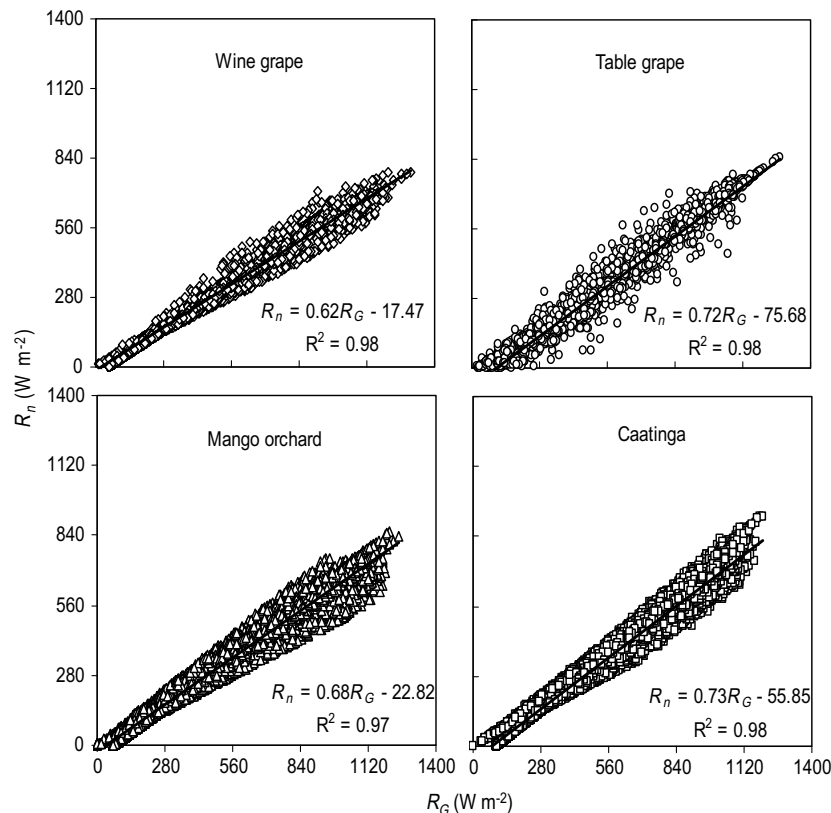


Figure 1 Relationship between net radiation (R_n) and global solar radiation (R_G) for 30 min time intervals during daylight hours for irrigated fruit crops (wine grape, table grape and mango orchard) and natural vegetation (Caatinga).

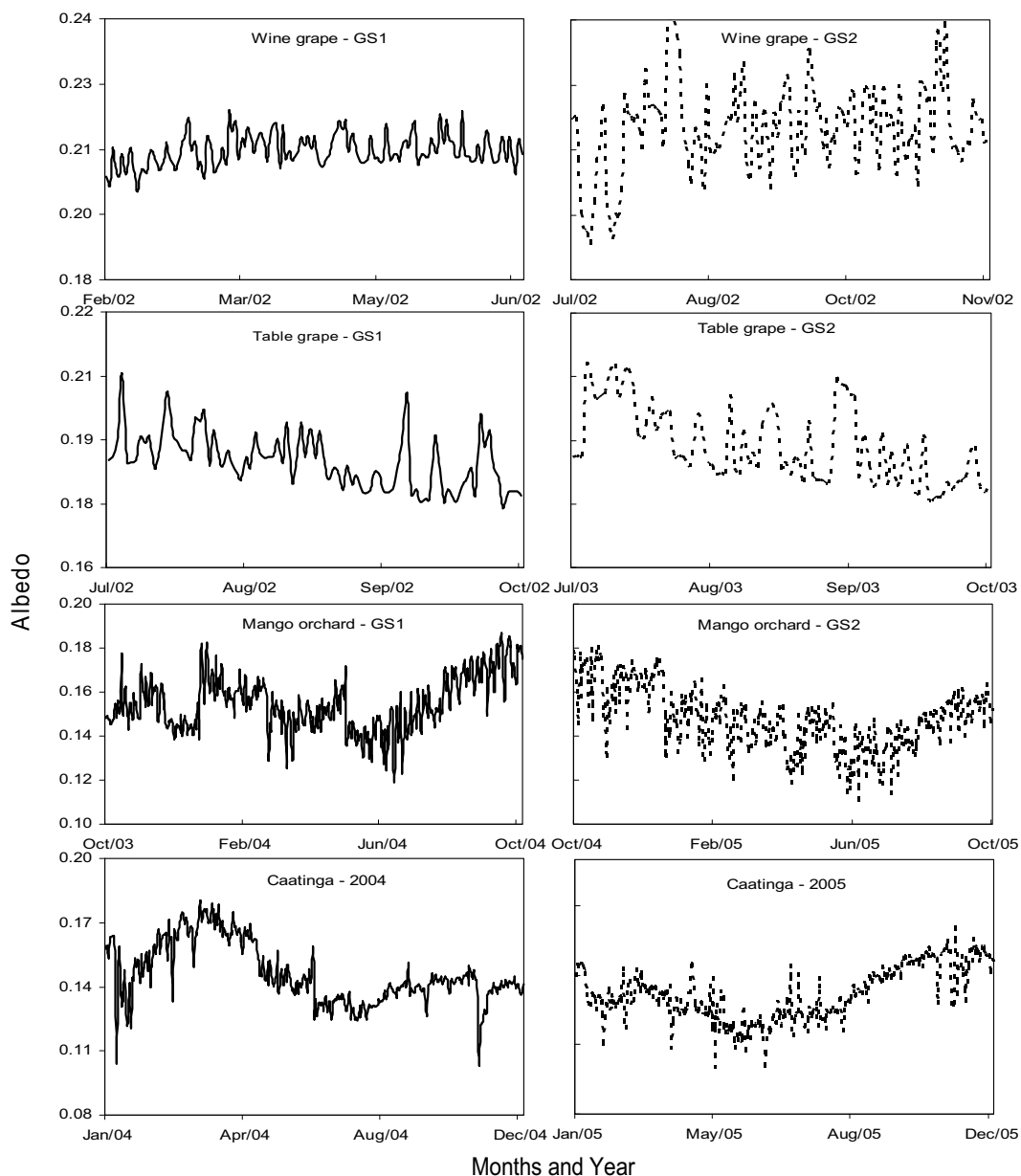


Figure 2 Seasonal variation of the surface albedo for the first (GS1) and second (GS2) growing seasons of irrigated crops: (a) and (b) – wine grape; (c) and (d) – table grape; (e) and (f) – mango orchard and (g) and natural vegetation (h) – Caatinga.

this stage α_0 varied due to several cultural practices reaching the lower values at the senescence stage. Differences between the seasonal α_0 of wine and table grapes were further due to the different trellis systems and cultural management. Mango trees displayed variation in α_0 according to their phenological stages and time of the year. However, more variation occurred during the rainy season when leaves were alternatively wet and dry due to interception. Higher values occurred as the leaf area increased under these conditions. This is a normal feature (Oliver and Sene, 1992).

The variability of α_0 in caatinga can be mainly attributed to variation in surface moisture conditions due to rainfall. The amounts of rainfall were 720 and 340 mm for 2004

and 2005 respectively, concentrated from January to April. The long term average rainfall is about 570 mm yr^{-1} . Monteith and Unsworth (1990) reported α_0 values between 0.15 and 0.26 for natural vegetation, higher than those for caatinga, possibly because of different surface moisture conditions and background reflectivity. However, the caatinga values were similar to those (0.12–0.13) reported for tropical rain forest (Oguntoyinbo, 1970; Pinker et al., 1980; Shuttleworth, 1988). The modification of α_0 with moisture conditions is in agreement with several authors (Campbell and Norman, 1998; Lobell and Asner, 2002; Van Dijk et al., 2004; Li et al., 2006).

R_R represented on average 22% of R_G for wine grape, 19% for table grape, 16% for mango orchard and 14% for

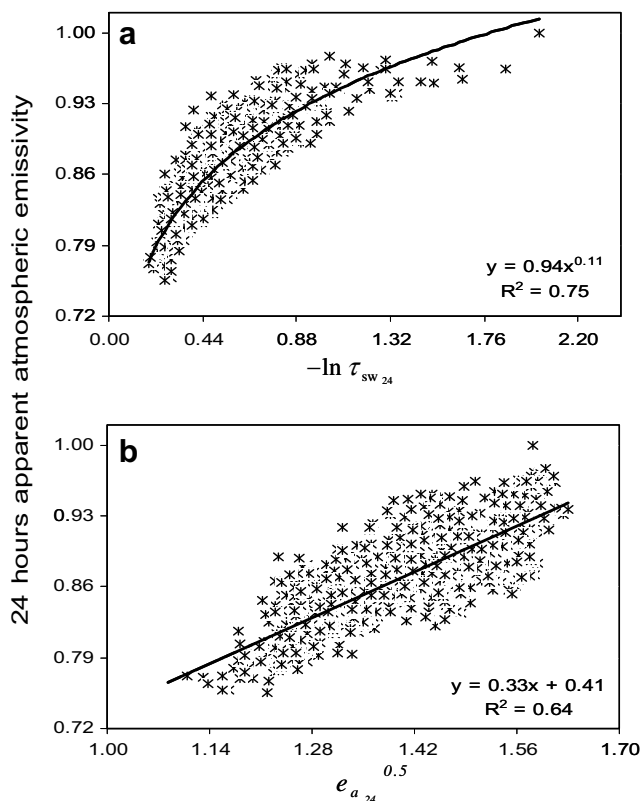


Figure 3 Relationships between apparent atmospheric emissivity with atmospheric transmissivity (a) and with actual air vapour pressure (b) for 24 h time scale.

caatinga, respectively (Table 1). Wine grape was the highest reflector out of the four agro-ecosystems investigated. This can be explained by the use of the vertical trellis system together with the exposure of the brightly reflecting soils to R_G . More oscillation in values during GS2 of wine grape could be attributed to the sun position and cloud free conditions in the second half of the year. The averaged albedo data for all vegetation of the current study were smaller than for those found in a rainfed vineyard (0.27) by Oliver and Sene (1992) on whitish calcareous soils.

The longwave radiation measurements over caatinga made it possible to estimate the 24 h apparent atmospheric emissivity (ϵ_a), which was in turn related to atmospheric transmissivity $-\tau_{sw}$ (Eq. (1)) as well as to actual vapour pressure $-e_a$ (Fig. 3a and b). The last relation followed the classical parameterization that is commonly applied for irrigated crops (Allen et al., 1998). The relationship with τ_{sw} appeared to be better ($R^2 = 0.75$) than for e_a ($R^2 = 0.64$). This is probably because the first parameter describes the overall conditions in the atmospheric column, rather than those at one given level near to the surface. The coefficients found for Eq. (1) ($a = 0.94$; $b = 0.11$) are in between the values obtained for Idaho ($a = 0.85$ and $b = 0.09$; Allen et al., 2000) and Egypt ($a = 1.08$ and $b = 0.26$; Bastiaanssen, 1995). The availability of ϵ_a made it feasible to compute R_{L1} at daily time scale.

Eq. (3) was tested because it allows the extrapolation of instantaneous to daily values of net radiation (R_{n24}). Fig. 4 shows that the fundamental basis of describing R_{n24} by means τ_{sw24} is valid; the overall agreement ($R^2 = 0.78$ –

0.83) is acceptable for semi-arid conditions of the São Francisco basin. The R_{n24} coefficient for all agro-ecosystems appears to be $a = 143$. In a grassland catchments area in the Netherlands, de Bruin and Stricker (2000) used $a = 135$, while the original value was $a = 110$. The difference can be ascribed to differences in macroclimatic conditions.

Energy balance

Average daily values of the energy balances for entire growing seasons for irrigated crops and for two years in natural vegetation are summarized in Table 2. Near neutral atmospheric conditions predominated above the irrigated crops with the sensible heat flux (H) accounting for 13–20% of R_n . Most of R_n was partitioned into latent heat flux (λE), averaging, 79%, 89%, and 77%, for wine grape, table grape and mango orchard, respectively. The correspondent values of the evaporative fraction (E_F) ranged from 0.73 to 0.89. Not surprisingly, the intensively irrigated table grapes exhibited the highest λE and E_F values.

Due to the vertical trellis system that resulted in more exposed soil between the rows, lower values of E_F were found for wine grape than for table grape. The experiments in wine grape involved growing seasons with different solar angles. The 24 h averaged value of G in wine grape was negative for the first half of the year, while during the second half G was positive. This indicates heating of the ground during the second growing season, as a result of the apparent movement of the sun associated to the vertical trellis system (see Table 2). Changes from negative to positive values of G were also reported by Li et al. (2006) for the steppe of Mongolia, when seasonal energy partition was analyzed. Differences in the partition of the energy balance with different trellis and crop-training systems in vineyards were also reported by Novello et al. (1992), Heilman et al. (1996) and Rana et al. (2004).

While the values of λE for mango orchard exceeded those for wine grapes (not for table grapes), the E_F values were lower. These differences could be ascribed to the lower α_0 of mango that resulted in greater R_n values. For both seasons of table grape and mango orchard G was negative, while for natural vegetation for both years it was nearly zero. Negative values indicated that the ground was an energy source to the atmosphere.

The caatinga natural ecosystem characteristics were manifested in low values of both E_F and λE rates. Despite the relatively high values for R_n , the λE was low implying in a greater part of available energy being partitioned as H . During the dry season, the air above caatinga received more heat than water vapour, resulting to warmer air layers. During the rainy seasons, R_n was essentially converted into λE , however these periods were short and for the annual scale, H exceeded λE .

A classical problem in energy balance modelling is the conversion from instantaneous components of this balance to daily values. The most common procedure is to compute instantaneous E_F , and consequently apply the same value for the entire day (e.g. Brutsaert and Sugita (1992), Bastiaanssen (1995), Su (2002) and Wang et al. (2007)). Literature on temporal variation of E_F has reported that the constant-value approach has an acceptable accuracy (e.g. Crago (1996)). Farah and Bastiaanssen (2004) demonstrated that there could be a deviation on a particular day, but that it

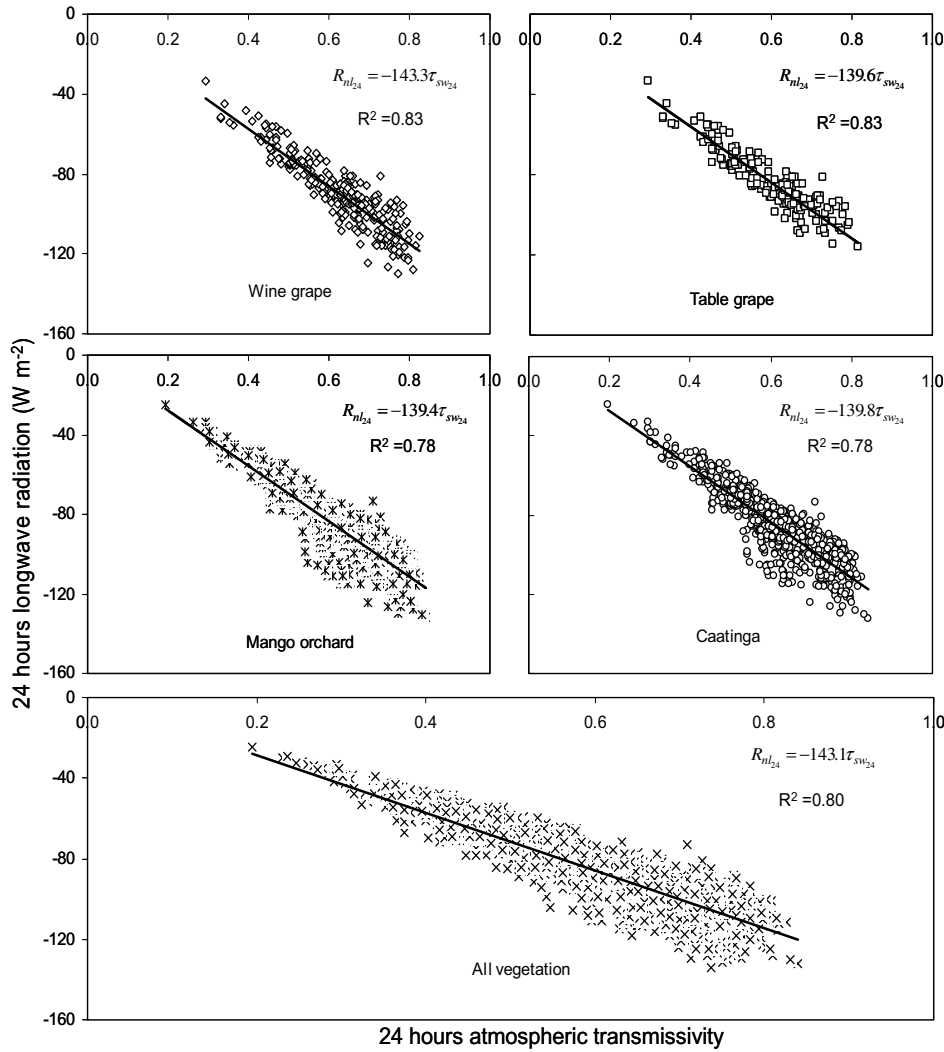


Figure 4 Relationships between net long wave radiation (R_{nl24}) and atmospheric transmissivity τ_{24} on a 24 h basis. The value of the vertical axis expresses the a-coefficient of Eq. (4).

Table 2 Averaged daily (24 h) energy balance for irrigated crops (Wine Grape – WG, Table Grape – TG, Mango orchard – MG) for the first (GS1) and second (GS2) growing seasons and for natural vegetation (Caatinga – CT) for two years (2004 and 2005): net radiation (R_n), latent heat flux (λE), sensible heat flux (H), soil heat flux (G) and evaporative fraction ($E_F = \lambda E / (R_n - G)$)

Vegetation/period	R_n ($\text{MJ m}^{-2} \text{d}^{-1}$)	λE ($\text{MJ m}^{-2} \text{d}^{-1}$)	H ($\text{MJ m}^{-2} \text{d}^{-1}$)	G ($\text{MJ m}^{-2} \text{d}^{-1}$)	E_F (-)
WG_GS1	9.77	8.07	1.90	-0.20	0.81
WG_GS2	10.31	7.73	2.08	0.50	0.79
TG_GS1	11.60	10.57	1.32	-0.29	0.89
TG_GS2	10.96	9.46	1.58	-0.08	0.86
MG_GS1	10.58	8.45	1.38	-0.37	0.77
MG_GS2	11.09	8.19	1.72	-0.18	0.73
CT_2004	11.56	4.62	5.69	0.03	0.40
CT_2005	10.78	2.67	6.88	0.03	0.25

can be used to acquire ET_a on weekly to monthly time scales.

The seasonal variations of E_F together the precipitations are shown in Fig. 5. During the growing seasons, vineyards were daily irrigated resulting to fairly constant values of

E_F as they were cultivated in periods with absence or low amounts of rains. In mango orchard the high values of E_F after the rains are evident as the growing seasons were longer involving the rainy periods. The natural vegetation has the ability to respond quickly to rainfall causing the values

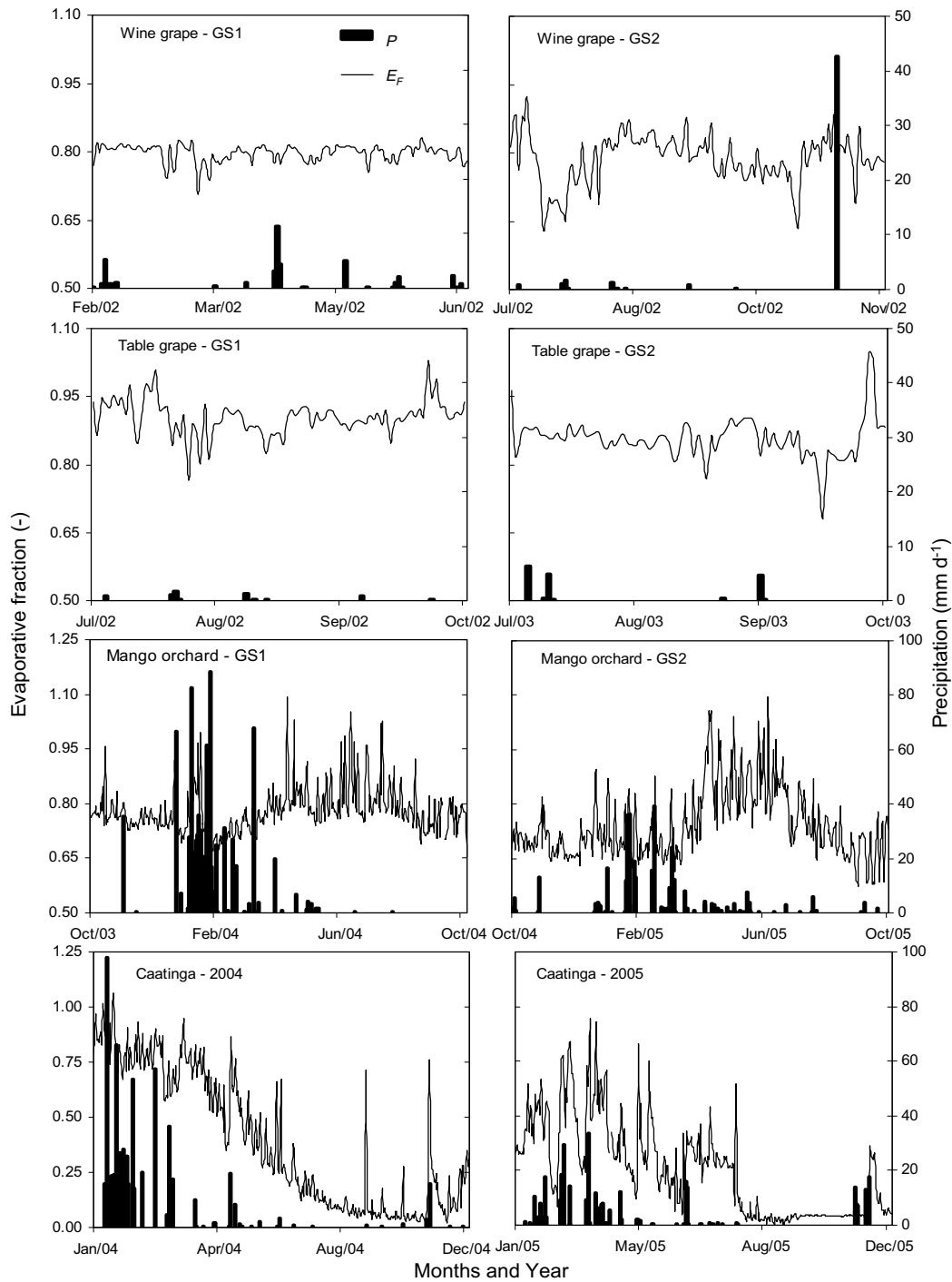


Figure 5 Seasonal variation of the evaporative fraction (E_F) and precipitation (P) for irrigated crops (Wine grape, table grape and mango orchard) and natural vegetation (caatinga).

of E_F high soon after the rains. The biggest effect was during 2004, when unusual precipitation occurred from January to April.

The 24 h ($E_{F_{24}}$) and daylight ($E_{F_{\text{daylight}}}$) values of evaporative fraction were calculated with the averaged values of R_n , λE and G for these time scales fulfilling $R_n > 0$ for daylight conditions. For midday ($E_{F_{12}}$), the instantaneous values at 12.00 h were considered (Fig. 6). The scatter in the graph with $E_{F_{12}}$ is larger than for $E_{F_{\text{daylight}}}$, because the latter repre-

sents a time integrated value that to a large extent affects the $E_{F_{24}}$. Yet, the values of $E_{F_{24}}$ are higher than those for $E_{F_{\text{daylight}}}$ for mango and caatinga. While for these two last vegetation a correction is necessary to acquire $E_{F_{24}}$ from $E_{F_{12}}$, for vineyards this is not. The implication is that E_F constancy varies with agricultural and natural ecosystems is an important finding for energy balance models at different time scales. Values of λE_{night} from eddy correlation measurements (mango orchard and caatinga) were higher than those

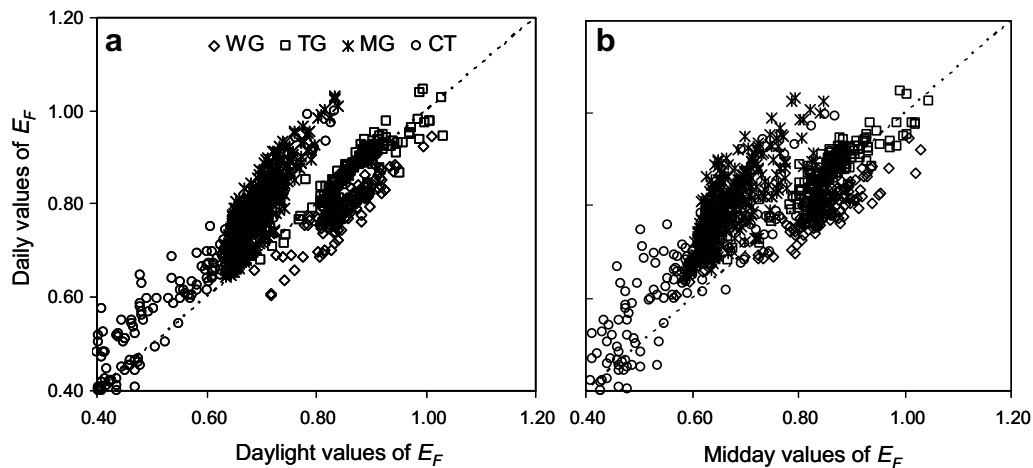


Figure 6 Relationships between the values $E_{F_{24}}$ vs. $E_{F_{\text{daylight}}}$ (a) and of $E_{F_{24}}$ vs. the noon-time $E_{F_{12}}$ values (b) for wine grape (WG), table grape (TG), mango orchard (MG), caatinga (CT) and for all these vegetation together.

from the Bowen ratio method (vineyards). This implies that grapes have more condensation than the first two types of vegetation. Whether this is a true observation or a consequence of the different micro-meteorological measurements has not been further investigated. The values of λE_{night} in mango orchard and caatinga contribute to a higher $E_{F_{24}}$.

Soil-vegetation parameterizations

Momentum roughness parameters

The seasonal (irrigated crops) and annual (natural vegetation) averaged measurements of the key vegetation parameters related to evapotranspiration are shown in Table 3.

Due to the tall and aerodynamically rough canopy architecture, mango orchard presented the greatest values of u_* . The averaged value was 0.49 m s^{-1} , much greater than for wine grape (0.21 m s^{-1}). The average z_{0m} value for wine grape was 0.08 m and for table grape 0.24 m . Sene (1994) reported values ranging from 0.04 to 0.06 m for rainfed wine grape growing under semi-arid conditions in Castilla

La Mancha with larger spacing within and between the rows ($5 \text{ m} \times 5 \text{ m}$). Van den Hurk et al. (1996) showed for the same region in Spain (but at a different plot) values from 0.01 m to 0.06 m , varying proportionally to the leaf area index (LAI). The maximum value seems to be in good agreement with our wine grape results. Table grape has a rougher surface than wine grape, and thus a larger z_{0m} that generates more turbulent movement above the canopy.

Although the mean value of z_{0m} for table grape was higher than for wine grape, the variations along the growing seasons were lower. The standard deviation for z_{0m} was 0.04 m in wine grape vineyard and only 0.01 m in the table grape vineyard (Fig. 7). The vertical trellis system with a low LAI in wine grape showed results that depended on the wind direction. When the wind blew more parallel to the rows (115°) z_{0m} values were 50% of those when the wind direction was near south-east (130°). Table grape was insensitive to changes in wind direction (see Table 3). Hicks (1973) reported that the drag coefficient doubled as the wind direction swung from parallel to normal of the vine rows in

Table 3 Average values of the vegetation parameters of irrigated crops (Wine Grape – WG, Table Grape – TG, Mango orchard – MG), for the first (GS1) and second (GS2) growing seasons and for natural vegetation (Caatinga – CT) for 2004 and 2005: aerodynamic (r_a) and surface (r_s) resistances; friction velocity (u_*); roughness lengths for momentum transfer (z_{0m}); mean vegetation height (h_v); vapour pressure deficit (D), wind speed above the canopies (u) and wind direction (WD)

Vegetation/period	r_a (s m^{-1})	r_s (s m^{-1})	u_* (m s^{-1})	z_{0m} (m)	h_v (m)	D (kPa)	u (m s^{-1})	WD (Degrees)
WG_GS1	114	131	0.21	0.11	1.6	1.8	1.9	128
WG_GS2	109	125	0.21	0.06	1.6	2.1	2.1	116
TG_GS1	63	64	0.38	0.23	1.8	1.3	2.0	118
TG_GS2	66	82	0.40	0.24	1.8	1.2	2.1	138
MG_GS1	36	133	0.50	0.50	5.5	1.3	2.6	126
MG_GS2	37	133	0.48	0.54	5.5	1.3	2.4	124
CT_2004	53	1542	0.39	0.43	8.0	1.5	2.8	135
CT_2005	58	2332	0.39	0.33	8.0	1.5	2.9	132

The height of the anemometers was 1 m above the canopies of vineyards, while they were at 3 m above the canopies in mango orchard and caatinga.

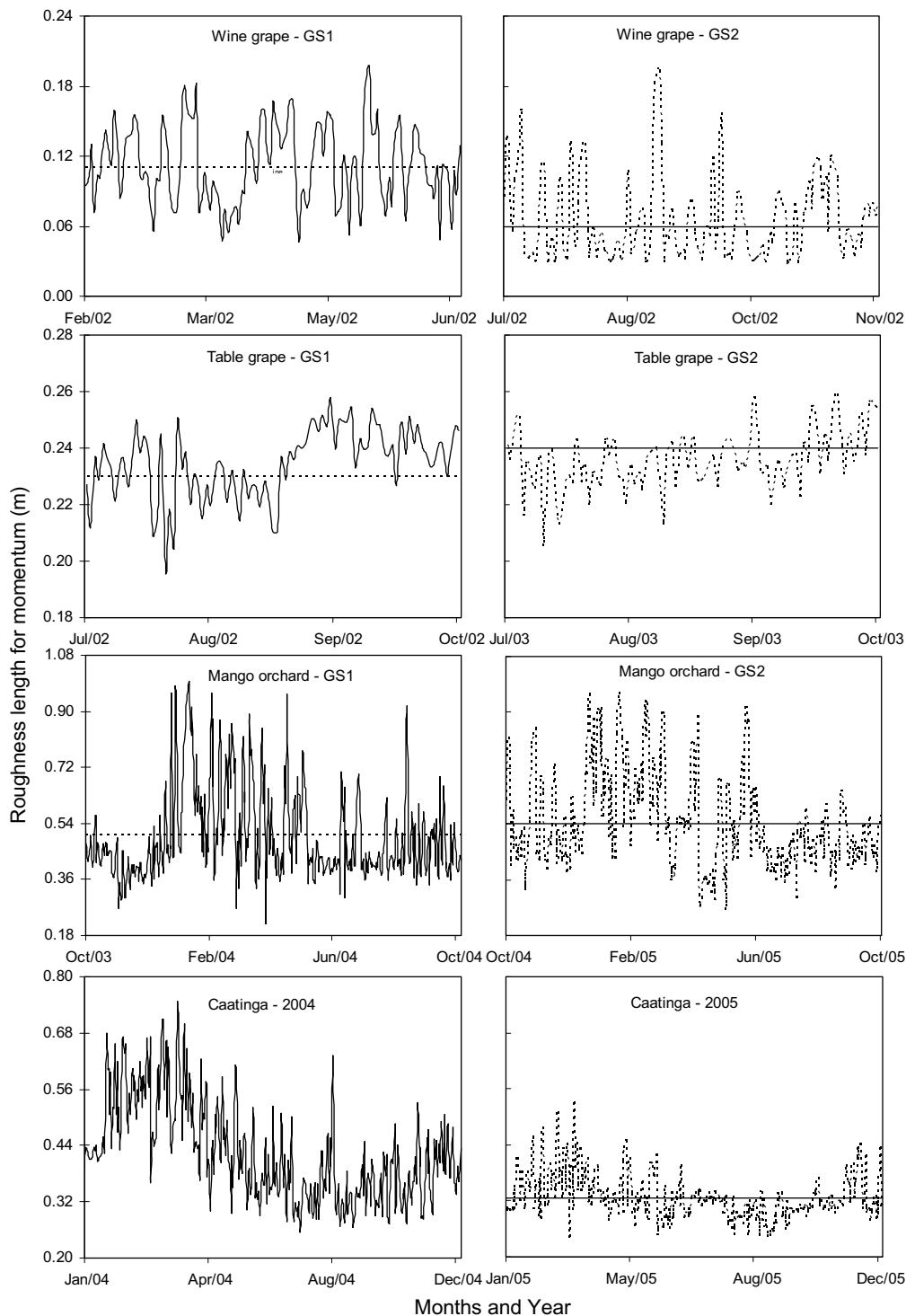


Figure 7 Seasonal variation of roughness length for momentum transfer (z_{0m}) for the first (GS1) and second (GS2) growing seasons of irrigated crops: (a) and (b) – wine grape; (c) and (d) – table grape; (e) and (f) – mango orchard and for 2004 and 2005 of natural vegetation: (g) and (h) – caatinga. Horizontal bars are averaged values.

vertical trellis. When they blew normal to the rows, z_{0m} was found to be about 13% of the vineyard height, behaviour typical for rough and closed canopies. In the present study, the horizontal overhead trellis of table grape covered almost all the soil beneath the canopy few days after bud break creating a rougher surface.

The z_{0m} values in the mango orchard averaged 0.52 m. The big crowns of the trees enhanced the momentum flux. The higher values of wind speed (u) above the canopy, if compared with vineyards, were due to the higher level of the anemometer. Despite the taller mixed species of caatinga (8 m) in relation to the trees of mango orchard

(5.5 m), results showed lower aerodynamic roughness values of z_{0m} (0.38 m) and u_* (0.39 m s^{-1}). The reason of these lower values can be explained by the patchwork of bushes and the irregular spacing among them. During an international land surface flux campaign on Sahelian bushland with irregular spacing among stripes of bushes, the values for z_{0m}

were also found to be at the lower side (0.22 to 0.27 m: Troufleau et al., 1997).

The z_{0m} values for mango orchard and for caatinga showed both effects from the rainy period (between January and March) which increases in leaf areas and thereby the surface roughness. More distinct differences in rough-

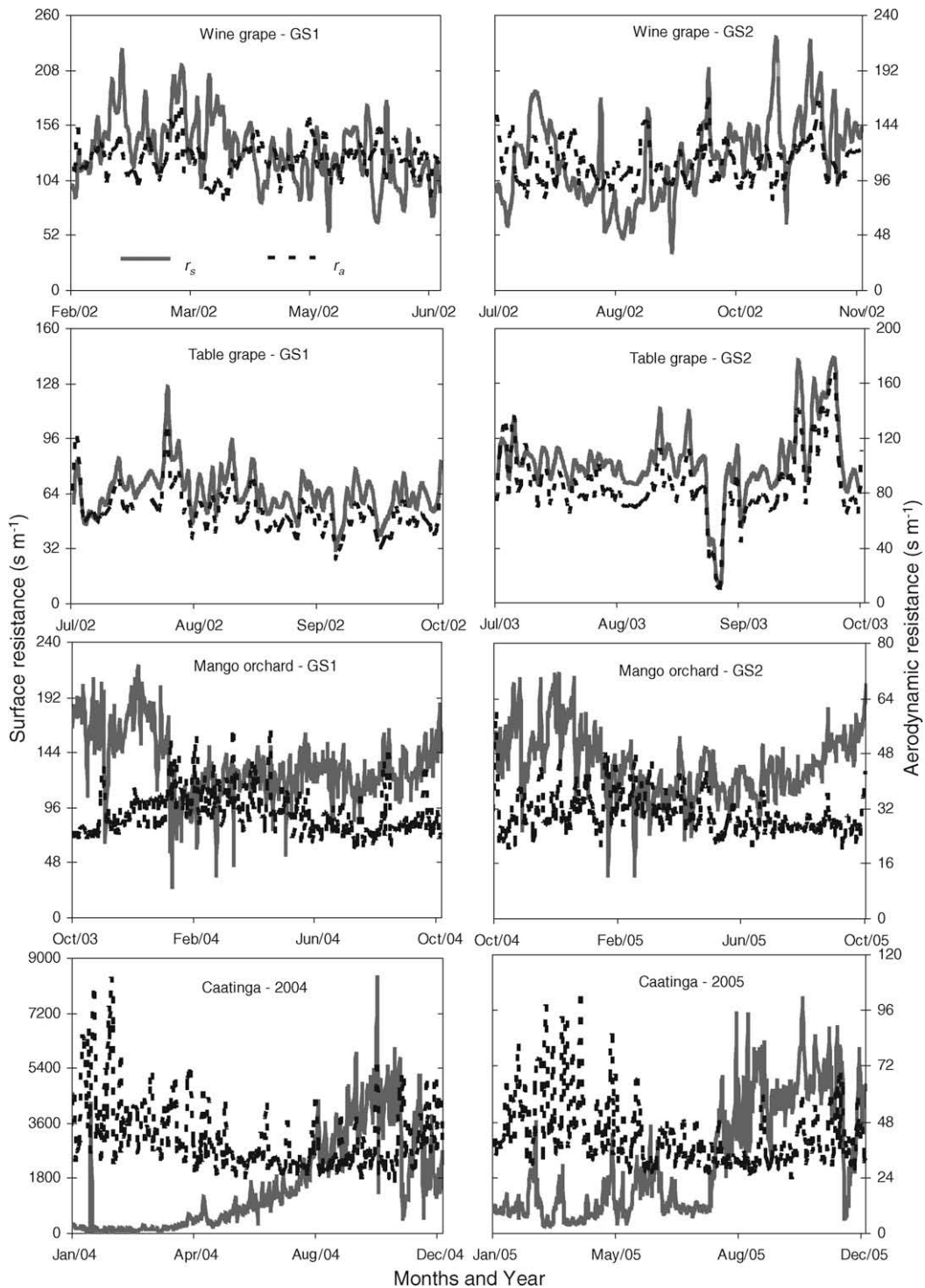


Figure 8 Seasonal variation of the bulk surface (r_s) and aerodynamic (r_a) resistances for the first (GS1) and second (GS2) growing seasons of irrigated crops: (a) and (b) – wine grape; (c) and (d) – table grape; (e) and (f) – mango orchard and for natural vegetation: (g) and (h) – caatinga.

ness parameters for natural vegetation were visible during 2004 than in 2005 (Fig. 7). This is related to the unusual high rainfall amount in 2004.

According to Sene (1994), sparse crops typically present z_{0m} values in the range 5–10% of the average vegetation height (h_v) while for uniform crops the values are typically about 13%. With our averaged values of z_{0m} of $0.06h_v$ for wine grape, $0.13h_v$ for table grape, $0.09h_v$ for mango orchard and $0.05h_v$ for caatinga, one can conclude that table grape is an exception due to its deviating canopy architecture. On average, z_{0m} is approximately 9% of the h_v .

Aerodynamic and bulk surface resistances

The seasonal-averaged values of resistances are shown in Table 3 while the seasonal variations are depicted in Fig. 8. Wine grape had the highest averaged value of r_a (112 s m^{-1}), followed by table grape (65 s m^{-1}), caatinga (55 s m^{-1}) and mango orchard (36 s m^{-1}). The low r_a for mango orchard is due to the aerodynamically rough canopy architecture evidenced by the highest values of u_* and z_{0m} . Wine grape presented less oscillation than table grape, as a result of the progressive coverage of the soil caused by the overhead trellis system together with several cultural practices along the growing seasons in the second vineyard. In the case of mango orchard, more vegetative growth during the rainy period promoted higher values of r_a due the increase of leaf area and z_{0m} . For caatinga, this effect also occurred, but more accentuated.

The maximum values of r_s among the vegetation types studied were detected in caatinga (mean r_s is 1937 s m^{-1} , see Table 3). The low moisture conditions during the dry season caused the stomata to close preventing the plant

from cell moisture depletion and wilting. Wine grape and mango trees presented similar r_s values around 130 s m^{-1} , while table grape r_s values were as low as 74 s m^{-1} . Table grape has almost a double LAI compared to wine grape. The lower value of D in micro sprinkler irrigation system also contributed to lower r_s values.

The daylight variation of r_s and D are shown in Fig. 9. Low values during the early morning represented the dominance of energetically dependent physiological control over λE . The greatest variation occurring at this time of the day is because r_s is close to its minimum value, partially due to dew (van Dijk et al., 2004). The low and near-minimum values for r_s only hold when all environmental conditions are optimal at the same time. Such pre-requisite does not last long, and a quick rise of r_s during morning hours is envisaged. The progressive soil moisture constraints and rising T_a and D induce stomatal closure. The higher values of r_s during the late afternoon are mainly related to the constraints induced by high T_a and D , in conjunction with lower levels of R_G . It is thus a combined effect, and no single responsible variable can be determined. The globally accepted standard ecological theories first presented by Jarvis (1976) and Stewart (1989) are herewith confirmed.

Fig. 9 suggests that the daylight behaviour of $r_s = f(D)$ is most tight for caatinga. The likely reason for this is the control of θ on stomatal regulation. While the irrigated crops experience diurnal cycles in root zone water availability, caatinga responds stronger to rainfall regime. Baldochi et al. (2004) observed the same phenomena for an oak, grass and savannah landscape. The relationships between r_s and D at a daily time scale throughout the measuring period are shown in Fig. 10. Except caatinga ($R^2 = 0.39$), irri-

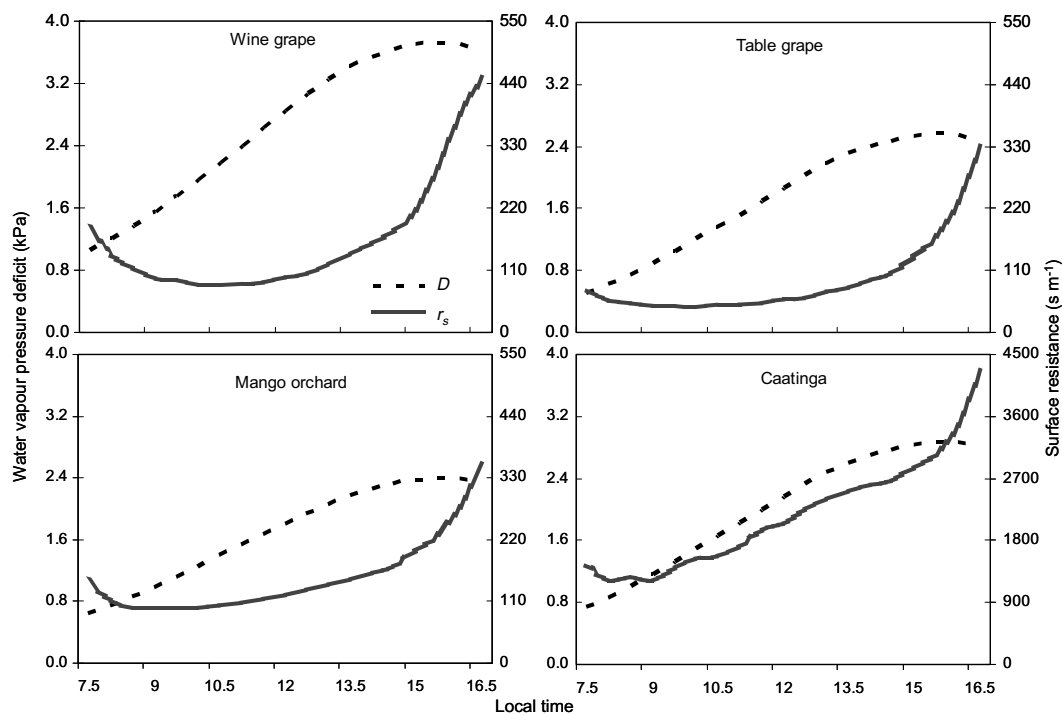


Figure 9 Daylight fluctuation of bulk surface resistances – r_s and vapour pressure deficit – D for irrigated crops (wine grape, table grapes and mango orchard) and natural vegetation (caatinga).

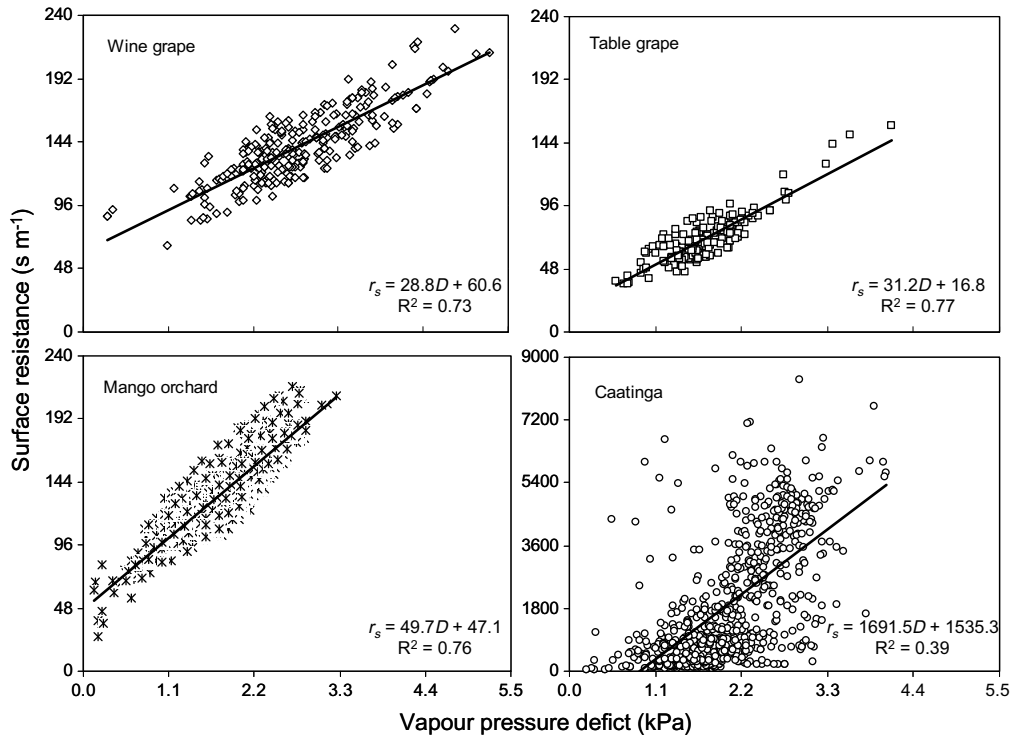


Figure 10 Daylight relationships between surface resistance (r_s) and vapour pressure deficit (D) for irrigated crops (Wine grape, table grapes and mango orchard) and natural vegetation (Caatinga).

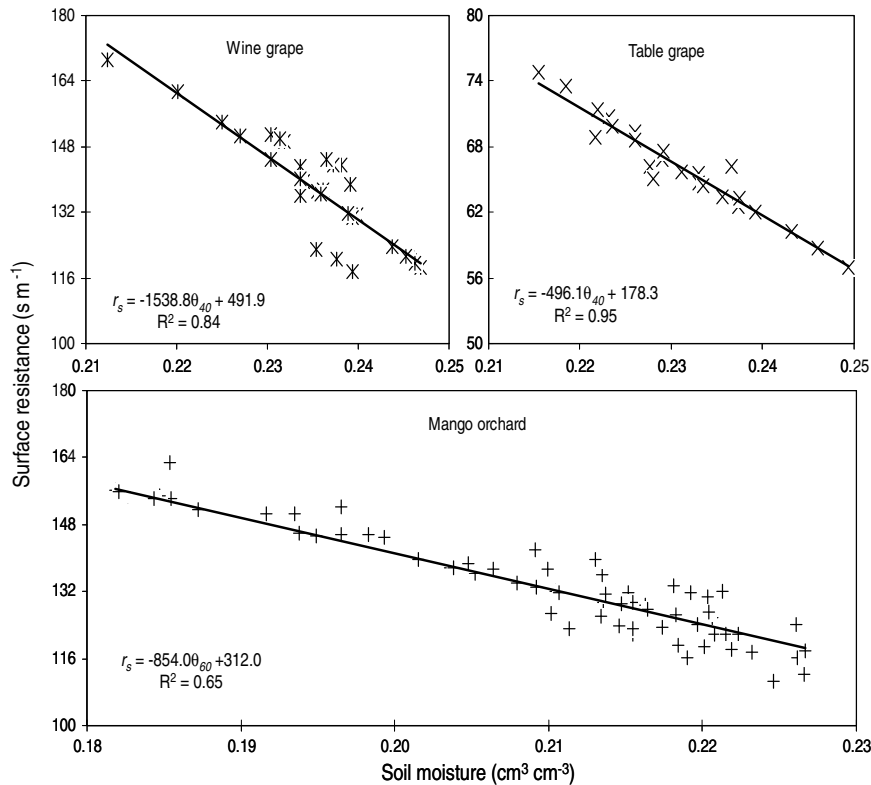


Figure 11 Weekly relationships between surface resistance (r_s) and soil moisture in irrigated vineyards for 40 cm soil depth (θ_{40}) and mango orchard for 60 cm soil depth (θ_{60}).

gated vineyards and mango showed a high correlation. While there were higher water vapour gradients between the sto-

mata and the near-surface atmosphere in dry periods, these gradients at the same time induced partial stomatal

closure. There is thus a negative feedback system in agroecosystems that dampens any significant variation in λE .

The effect of θ on r_s is evident when studying their relationships for irrigated fruit crops (Fig. 11). While the r_s of caatinga was dominantly controlled by seasonal soil moisture variability, in irrigated fruit crops it was controlled by both θ ($R^2 = 0.65\text{--}0.95$) and D ($R^2 = 0.73\text{--}0.77$). Mango was more responsive to D ($R^2 = 0.76$) than to θ ($R^2 = 0.65$). Hence, ET_a and water productivity in this orchard are largely influenced by D levels. The role of on-farm irrigation management in vineyards need thus to be done more alert than in mango orchards. One can practice very precise irrigation, but the water balance in mango orchards will be influenced by D .

The r_s response to θ was published for alfalfa by van Bavel (1967) and for wheat by Hatfield (1985). Larger changes of r_s occur at small changes in wet soils. At an average soil water content of $0.20 \text{ cm}^3 \text{ cm}^{-3}$, the sensitivity of table grapes is $dr_s/d\theta = 496$ for wine grapes, $dr_s/d\theta = 1539$ for wine grape, $dr_s/d\theta = 853$ for mango orchard, $dr_s/d\theta = 80$ for wheat (Hatfield, 1985) and $dr_s/d\theta = 350$ for alfalfa (van Bavel, 1967). The highest slopes of $dr_s/d\theta$ reveal the strongest response to changes in available soil water. Wine grape thus exhibits the strongest response of r_s to minor changes of θ , followed by mango, table grape, alfalfa and finally wheat.

Conclusions

The diurnal and seasonal variation of the radiation and energy balance components in irrigated crops and natural vegetation in the Brazilian semi arid region of Sao Francisco River basin have been investigated. These investigations allowed a better understanding of the energy fluxes and the physical vegetation properties that affect these exchange processes, what are important for appraising the impact of land use changes on the regional scale water balance. From radiation measurements, it could be concluded that net radiation can be estimated by means of a linear expression with global solar radiation depending on the type of vegetation. The presented equation to estimate apparent emissivity of the atmosphere from atmospheric transmissivity had a better correspondence with field measurements than the standardized FAO equation based in actual vapour pressure. The atmospheric emissivity estimation is fundamental for the estimation of instantaneous net radiation fluxes.

The daily values of evaporative fraction (E_F) for all irrigated crops varied between 0.71 (mango orchard) to 0.90 (table grape), revealing that most net available energy ($R_n - G$) is converted into actual evapotranspiration. This implies that the atmospheric boundary layer over wet irrigated perimeters receives small quantities of sensible heat, and stays thus relatively cold. The E_F values of caatinga, the natural vegetation, were in an annual scale with 0.25–0.40 much smaller than for irrigated crops. A distinct seasonal variation of E_F in caatinga was found because of the water availability linked to precipitation patterns during the year.

It was demonstrated that daytime and daily energy balances can be estimated from instantaneous measurements, provided that net radiation and soil heat flux are known

across time integrated periods. The energy balances for mango orchard and caatinga showed that a slight correction is required if the instantaneous E_F is to be used as a representative value for a 24 h period.

Parameterizations of the aerodynamic (r_a) and the bulk surface (r_s) resistances facilitated the analysis of the comprehensive evapotranspiration from heterogeneous land surfaces. The variability of r_a can be mainly explained by the friction velocity which on turn depended on the surface roughness length for momentum transport (z_{0m}). In wine grape, the vertical trellis system affected the roughness parameters according to the wind direction. The overhead trellis system in table grape was – due to the sheltering effect – less sensitive to wind direction. The experimental data showed that for sparse canopies, z_{0m} being 9% of the vegetation height is a doable operational rule for the semi-arid region of São Francisco River basin. For large spacing between clumps of caatinga, z_{0m} is reduced in comparison with irrigated fruit trees.

The r_s values for wet surfaces are dominantly affected by atmospheric water vapour pressure deficit (D) and soil moisture (θ). There was a negative physiological feedback from D on evapotranspiration rates: while high D values increased the gradient of water vapour transport, it at the same time created an extra blockade on the vapour flow path by partially closing the stomata. This negative feedback prevented vineyards and mango orchards from exhaling large quantities of water vapour what controls transpiration fluxes and increases the crop water productivity. Natural vegetation also showed a link between r_s and D but less than for irrigated crops; for long period, r_s in natural vegetation is determined predominantly by moisture conditions. The availability of analytical methods to assess r_a and r_s makes the one-step Penman–Monteith equation suitable for actual evapotranspiration and water productivity estimations. By further developing of methods to parameterize crop production at the regional scale, it will become feasible to estimate water productivity variations and detect areas where water saving in agriculture could be realized.

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