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Seasonal Evolution of the Evapotranspiration Regime and Carbon Assimilation Over a *Eucalyptus globulus* Plantation

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Abstract. Seasonal patterns of carbon assimilation and evapotranspiration of 2004 in *Eucalyptus globulus* plantation of the *CarboEurope-IP* Portuguese site of Herdade da Espirra are discussed. The atmospheric fluxes were obtained by the eddy covariance method. A separation of atmospheric carbon flux, or net ecosystem exchange (*NEE*), in gross primary production (*GPP*) and ecosystem respiration (R_{eco}), was made and analysed the variation of atmospheric fluxes with some micrometeorological variables. The plantation acted as a strong carbon sink, with a *NEE* of 7.9tonC.ha^{-1}.yr^{-1}. The diurnal *NEE* was mainly a function of global solar radiation, with which it is perfectly in phase all year around, except for the period between July and September. In these months, stomatal closure, strongly dependent on the water vapour pressure deficit in the atmosphere (*WVD*) high values and low water availability, was the main factor controlling carbon assimilation, a tendency already noticed in 2002 and 2003. The evapotranspiration is clearly controlled by water vapour deficit with decoupling factors (Ω) varying from 0.1 to 0.4, typical data for forest canopies. In the period from July to September evapotranspiration dependency on *WVD* increases as a consequence of the stomatal closure.
Key words: seasonal patterns; evapotranspiration; carbon; radiation; vapour pressure

Evolução Sazonal dos Regimes de Evapotranspiração e da Assimilação do Carbono numa Plantação de *Eucalyptis globulus*

Sumário. São discutidos os padrões sazonais de assimilação de carbono e do regime de evapotranspiração numa plantação de *Eucaliptus globulus* no site de Herdade da Espirra do Programa Europeu CarboEuroflux. Os fluxos atmosféricos foram obtidos pelo método de covariância turbulenta. Foi estabelecida a decomposição do fluxo de carbono atmosférico ou balanço líquido de carbono nas componentes de respiração do ecossistema e produção primária bruta e analisada a variação dos fluxos com alguns parâmetros meteorológicos. A plantação funcionou como sumidouro substancial de carbono, à taxa de 7.9tonC.ha^{-1}.ano^{-1}. O balanço líquido diurno foi especialmente dependente da radiação solar global, em regime de fase concordante ao longo de todo o ano, exceptuando o período entre Julho e Setembro. Nestes

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meses o encerramento dos estomas, fortemente dependente do elevado défice de pressão de vapor da atmosfera e baixo teor de água disponível, foi o principal factor de controlo da assimilação de carbono, tendência já evidenciada em 2002 e 2003. A evapotranspiração é claramente controlada pelo défice de pressão de vapor atmosférico com coeficientes de desacoplamento variando entre 0.1 e 0.4, valores típicos para cobertos florestais. No período compreendido entre Julho e Setembro a dependência da evapotranspiração relativamente ao défice de pressão de vapor aumenta em consequência do fecho dos estomas.
Palavras-chave: padrões sazonais; evapotranspiração; carbono; radiação; pressão de vapor

Évolution Saisonnière des Régimes d'Évapotranspiration et d'Assimilation de Carbone dans une Plantation d'*Eucalyptus globulus*

Résumé. Ci-après nous discuterons des modèles saisonniers d'assimilation de carbone et du régime d'évapotranspiration d'une plantation d'*Eucalyptus globulus* sur le site de la Herdade da Espirra et conformément au Programme Européen CarboEuroflux. Les flux atmosphériques ont été obtenus par la méthode de covariance turbulente. La décomposition du flux de carbone atmosphérique ou échanges de carbone liquides a été établie dans ses composantes, en respiration de l'écosystème et en production primaire brute. La variation des flux a été analysée suivant certains paramètres météorologiques. La plantation a fonctionnée comme un fort « puit » de carbone, présentant un taux de 7.9ton C.ha^{-1}.année^{-1}. Les échanges de carbone avec l'écosystème ont surtout été dépendants de la radiation solaire globale, en régime de phase concordante au long de toute l'année, sauf pour les mois de Juillet à Septembre, inclus. Pendant ces mois, la fermeture des stomates, fortement dépendante de l'élevé déficit en pression de vapeur atmosphérique ainsi que du bas taux d'eau disponible, a été le facteur principal du contrôle de l'assimilation du carbone, tendance déjà vérifiée en 2002 et en 2003. L'évapotranspiration est clairement contrôlée par le déficit de pression de vapeur atmosphérique présentant comme valeurs des coefficients de désaccouplement entre 0.1 et 0.4, valeurs typiques pour des couverts forestiers. Pendant la période comprise entre Juillet et Septembre la dépendance de l'évapotranspiration envers le déficit de pression de vapeur augmente due à la fermeture des stomates.
Mot clés: modèles saisonniers; évapotranspiration; carbone; radiation; pression de vapeur

Introduction

The *CarboEurope-IP* is a European Programme started in 2004 with the duration of 5 years that aims "to understand and quantify the terrestrial carbon balance of Europe and associated uncertainties at local, regional and continental scale" (http//www.carboeurope.org). The *CarboEurope* programme is sequential to the previous *CARBOEUROFLUX*, being mainly concerned with the role of terrestrial biosphere as carbon sink, and therefore with the influences of both climate changes and land use/management in the carbon cycle, clearly in the context of Kyoto Protocol.

The results presented in this paper are related with the study of both carbon and water vapour atmospheric fluxes, by eddy covariance, in 2004 at the *CarboEurope-IP* Portuguese ecosystem study site of Espirra (300 ha *Eucalyptus globulus* plantation). A description of the site, fluxes and meteorological data of 2002 and 2003 are indicated in RODRIGUES *et al*., 2005.

Presently, the studies in this site are mainly directed to the establishment of modelling relations between atmospheric fluxes and micro-climatological variables, namely global solar radiation, air temperature, water vapour pressure deficit and precipitation. The understanding of fluxes driving factors is also a useful instrument for optimizing the gap filling strategies of missing or inaccurate data.

Site description and methods

The Herdade da Espirra site is a 300ha *Eucalyptus globulus* plantation (38º38'N, 8º36'W), trees spacing 3x3m, with a mean canopy height of 20m, 11 years aged and an estimated leaf area index (*LAI*) of 2.47. The cover is located in a flat terrain, and it extends for distances from 700m to 1800m in several directions, from the measurement tower.

The micrometeorological data were recorded in an automatic weather station, described by RODRIGUES *et al.*, 2005. Water vapour pressure deficit (*WVD*) was obtained from air temperature (calculation of saturation vapour pressure) and relative humidity (hygrometer data). Data for fluxes and meteorological variables consisted of means over thirty minute periods. For precipitation, the values corresponded to integrals over the same length period.

This eddy covariance unit consisted of an ultra-sonic anemometer *Gill R2* and an open path CO_2/H_2O analyzer *IRGA Li-7500*. Calculation of the covariance for the mentioned averaging period, was done with block averaging; spike interpolation; WPL correction (WEBB *et al.*, 1980); SHOTANUS/LIU (SHOTANUS *et al.*, 1983 and LIU *et al.*, 2001) correction for sonic temperature: humidity and crosswind; SHOTANUS/LIU correction for sensible heat flux: buoyancy flux to sensible heat flux and crosswind.

To maximise the covariance between vertical wind velocity and the gas analyser signals, independent time lags for carbon dioxide and water vapour were determined. A planar fit coordinate rotation (WILCZAK *et al.*, 2001) for wind components was performed, calculating the angle for the rotation of the vertical wind component in a monthly basis.

As data quality control proceedings, fluxes calculated for periods with at least one of the following, where discarded for future considerations: mean vertical velocity deviation to zero higher than $0.35 m.s^{-1}$ (following the same principle as in REBMANN *et al.*, 2004), percentage of spikes above 1% (VIKERS and MAHRK, 1997), friction velocity (u_*) below the threshold of $0.2 m.s^{-1}$. The u_* threshold was determined graphically, by plotting nigh time CO_2 flux, grouped by classes u_*, against u_*. The threshold is the value above which the flux is independent of the friction velocity. In the case of the Espirra site the method works quite well, since there is not any evidence of pumping effects, either the u_* value varies along the year (problems described in GU *et al.*, 2005).

Data that fulfil the requirements described in the previous paragraph is submitted to stationarity test and integral turbulence characteristics test (FOKEN and WICHURA, 1996), and flagged according to the results (MAUDER and FOKEN, 2004).

In 2004 power failure was responsible for a high percentage of 59.5% for both missed and rejected data. After April, the substitution of batteries allowed an improvement of missed/rejected data to a percentage of 44.5% (35% for diurnal periods and 53% for nocturnal periods). Those values are better than the ones cited by RODRIGUES *at al.*, 2005 to the same site in 2002 and 2003 (39.9 and 56%

to the diurnal and nocturnal periods). The diurnal percentage is already close to the mean value (32.6%) of 18 sites (FALGE *et al.*, 2001). The nevertheless high value (53%) for nocturnal periods is due to very calm summer nights (friction velocity less than 0.2m.s^{-1}).

Gap filling for carbon and water vapour fluxes was applied using the online calculation software in (http://gaia.agraria.unitus.it/database/ eddyproc) that combines look up tables and mean diurnal variation methodologies.

Net ecosystem exchange is obtained by the following equation:

$$NEE = F_c + F_{\Delta S} + F_A \tag{1}$$

where $F_c = \overline{w'c'}$ is the covariant flux of CO_2, $F_{\Delta S}$ is the change in storage of CO_2 in the soil-air volume beneath the tower and F_A is the advection term. According to SCHMID *et al.*, 2000, data of measured fluxes for the prevalent conditions may be considered as data of *NEE*. However, for storage, one point calculation was performed, according to GRECO and BALDOCCHI 1996.

Net ecosystem exchange (*NEE*) relates to gross primary production (*GPP*) and ecosystem respiration (R_{eco}) by the equation:

$$GPP = NEE - R_{eco} \tag{2}$$

Calculation of ecosystem respiration allowing partitioning of *GPP* was made online (http://gaia.agraria.unitus.it/database/ eddyproc) by adjustment of Loyd-and-Taylor regression model (REICHSTEIN *et al.*, 2005):

$$R_{eco} = R_{ref} \cdot e^{E_0 \cdot \left(\frac{1}{T_{ref} - T_0} - \frac{1}{T - T_0} \right)} \tag{3}$$

with E_0 and R_{ref} being the activation energy and respiration at reference temperature (T_{ref}), of 10ºC and T_0 a constant temperature of -46.02ºC. Variables E_0 and R_{ref} are calculated by adjustment of *NEE* night values (or respiration since photosynthetic activity stops) and air temperature (*T*).

Big-leaf approach was used to analyse plant response to water availability and atmospheric moist conditions, in this case with the objective of identify the stomatal control on carbon uptake.

This concept presents the capacity of checking the direct vegetation response by using the flux data, in this case water vapour flux. This flux, taken as evapotranspiration, was used to calculate the canopy resistance (r_c), by inversion of Penman-Monteith equation (MONTEITH and UNSWORTH, 1990):

$$E = \frac{\Delta(R_n - G) + \frac{\rho c_p WVD}{r_a}}{L\left[\Delta + \frac{\gamma(r_c + r_a)}{r_a}\right]} \tag{4}$$

The value of E is the evapotranspiration as measured by eddy covariance; Δ is the rate of change of saturation water vapour pressure with temperature in Pa.K^{-1}; R_n is the net radiation in W.m^{-2}; G is the soil heat flux in W.m^{-2}; ρ is the specific air mass, considered constant at 1 kg.m^{-3}; c_p is the specific heat at constant pressure of air, considered constant at 1010 J.kg^{-1}.K^{-1}; *WVD* is the water vapour pressure deficit (Pa); r_a is the aerodynamic resistance in s.m^{-1}; L is the heat of vaporization of water, assumed constant at 2465×10^3J.kg^{-1} (corresponding to a T of 15ºC); and γ is the psychometric constant in Pa.K^{-1}. The *WVD* calculation was determined by equation (5), with air temperature T given in ºC:

$$e_s(T) = 611\,exp\left(\frac{17.502T}{T+240.97}\right) \quad (5)$$

Soil heat flux was obtained by energy balance as follows:

$$G = R_n - (H + LE) \quad (6)$$

Aerodynamic resistance was calculated with equation (7), since the friction velocity is $u_* = \sqrt{\tau / \rho}$, where τ is the co-variant momentum flux ($\tau = -\rho\overline{u'w'}$), and u is the mean horizontal wind velocity:

$$r_a = \frac{u}{{u_*}^2} \quad (7)$$

In malfunctioning periods of the eddy covariance unit, r_a was calculated according to the equation (8):

$$r_a = \frac{\left[ln\left(\frac{z-d}{z_0}\right)\right]^2}{uk^2} \quad (8)$$

Where z is the height of wind velocity measurement (33m), d is the zero displacement height, z_0 is the surface roughness and k is the Von Karman constant (0.41).

An algebraic manipulation of equation (4) by McNAUGHTON and JARVIS 1983 resulted in:

$$E = \Omega\frac{\Delta(R_n - G)}{L(\Delta+\gamma)} + (1-\Omega)\frac{WVD}{r_a + r_c} \quad (9)$$

Where Ω is the dimensionless decoupling coefficient. Equation (9) parts equation (4) in two components. The first term on the left side is the so called equilibrium evaporation, LE_{eq}, representing the evaporation that would occur if the energy budget would be dominated by the radiative term. The second term of the right side is the imposed or coupled evaporation, resulting from an effective control of the evaporative process by the local weather. Equilibrium evaporation prevails in situations of short vegetation, bright sunshine, low wind and light wind. Coupled evaporation is dominant in situations of high vegetation, such as forest canopies and strong winds.

The Ω coefficient is defined as:

$$\Omega = \frac{\frac{\Delta}{\gamma}+1}{\frac{\Delta}{\gamma}+1+\frac{r_c}{r_a}} \quad (10)$$

In equation (10) r_c is calculated by inversion of Penman-Monteith equation, using evapotranspiration obtained by eddy covariance. Typically Ω is of order of 0.1 to 0.2 in forest canopies in contrast with 0.8 to 0.9 on short vegetation. In aerodynamically rough forest canopies or high turbulence periods (low values of r_a) a strong coupling to atmospheric humidity occurs. The atmospheric coupling extends to the convective boundary layer scale (BLANKEN *et al.*, 1997). Authors like BALDOCCHI *et al.* 1997 argue that long term factors, such as biogeochemical processes, associated to nutrient cycling and organic decomposition, interact with short term ones such as the atmospheric vapour deficit or other physiological factors in the dynamics or stomatal opening.

Results and discussion

The monthly data for means and standard deviations of daily integrals of global solar radiation, mean air temperature and noon water vapour deficits (*WVD*) are given in Table 1. Table 2 shows monthly data of mean and standard deviations for net ecosystem exchange, ecosystem respiration and evapotranspiration *E* (water vapour covariant fluxes). The three months with higher *WVD* (July to September) are the ones with lowest *NEE*. Such a summer depression for *NEE* in the same site was also indicated by RODRIGUES *et al.*, 2005, for 2002 and 2003. The same period also shows a decrease in *E*, giving evidence that the depression in carbon uptake is associated to stomatal closure in order to counter the atmospheric water vapour deficit and a likely shortage of soil water for the eucalypt trees.

Table 1 - 2004 monthly means and standard deviations for day integrals of global solar radiation, (kJ.m-2.day-1), day means of air temperature (ºC) and noon WVD (Pa)

	Global Solar Radiation		Air Temperature		WVD	
Month	**Mean**	**Std. dev.**	**Mean**	**Std. dev.**	**Mean**	**Std. dev.**
January	6601	3593	10.9	2.4	522.1	216.2
February	10460	3256	10.0	3.0	615.1	258.7
March	15252	5549	10.1	2.3	604.6	237.7
April	21700	5389	11.7	2.2	633.7	180.1
May	22442	5906	14.3	3.1	708	195.3
June	27894	3331	20.1	2.5	1670.7	1045.6
July	27752	2756	21.4	3.4	2898.5	1313.3
August	22675	4289	20.6	1.3	1985.8	794.2
September	18711	3215	19.1	1.8	2085.2	1044
October	11766	4699	15.4	2.8	1087.5	827.5
November	9964	2988	11.1	2.3	700.8	296.4
December	8489	2050	9.2	2.3	554.7	156.7

Table 2 - Monthly mean and standard deviations of integrals net ecosystem, ecosystem respiration, ($kgC.ha^{-2}.day^{-1}$) and evapotranspiration ($ton.ha^{-2}.day^{-1}$)

	NEE		E		R_{eco}	
Month	**Mean**	**Std. dev.**	**Mean**	**Std. dev.**	**Mean**	**Std. dev.**
January	-25.0	8.7	9.5	4.1	2.3	4.4
February	-39.5	13.8	12.3	2.9	8.0	9.6
March	-19.2	12.1	14.0	3.8	29.1	8.3
April	-43.2	14.0	27.5	7.6	18.2	11.0
May	-32.5	18.1	27.9	6.7	32.9	15.7
June	-29.3	8.4	30.2	3.2	34.2	4.1
July	-24.4	18.0	20.3	3.8	25.7	4.8
August	-11.2	9.2	15.6	3.9	24.0	3.8
September	-4.5	9.0	13.0	4.2	23.2	4.2
October	-9.1	10.6	12.1	4.6	19.0	5.9
November	-12.0	9.9	14.3	3.7	28.3	6.4
December	-26.8	17.0	15.6	5.3	14.5	7.9

The carbon annual uptake was 7.9tonC.ha^{-1}.yr^{-1}, with a monthly distribution shown in Figure 1. Such value is slightly lower than the 9.3tonC.ha^{-1}.yr^{-1} obtained in 2003, data reported in RODRIGUES *et al.*, 2005.

Since ecosystem respiration data are less variable from March to November (standard deviation (171Kg.ha^{-1}) corresponding to 21% of the mean value for the same period (796Kg.ha^{-1})), than those of *NEE*, the referred summer depression is mainly due to a diminishing in the carbon uptake.

Considering daily values, above 18ºC occurred a notorious restraining in the increase of ecosystem respiration (Figure 2), due possibly to the effect of augmenting hydric stress in the reducing of metabolic activities. Concomitant with the previous verification, *Reco* is positively related with evapotranspiration (Figure 3).

The comparison between precipitation and evapotranspiration also confirms the hydric stress felt by the ecosystem, since its integrals for the period between October 2003 and September 2004 are respectively 530mm and 640mm, indicating that the evapotranspiration is 21% higher. This hydric stress is likely circumvented by the profound and complex root system of trees allowing them to search water deep in soil.

The annual diurnal variation of Ω for 2004 is shown in Figure 4. The mean Ω value was lower during the summer below 0.2 from June to October and reaching 0.4 in the rest of the year.

This is a direct consequence of increased stomatal resistance due to the increment of *WVD* with a reinforcement of imposed evapotranspiration component.

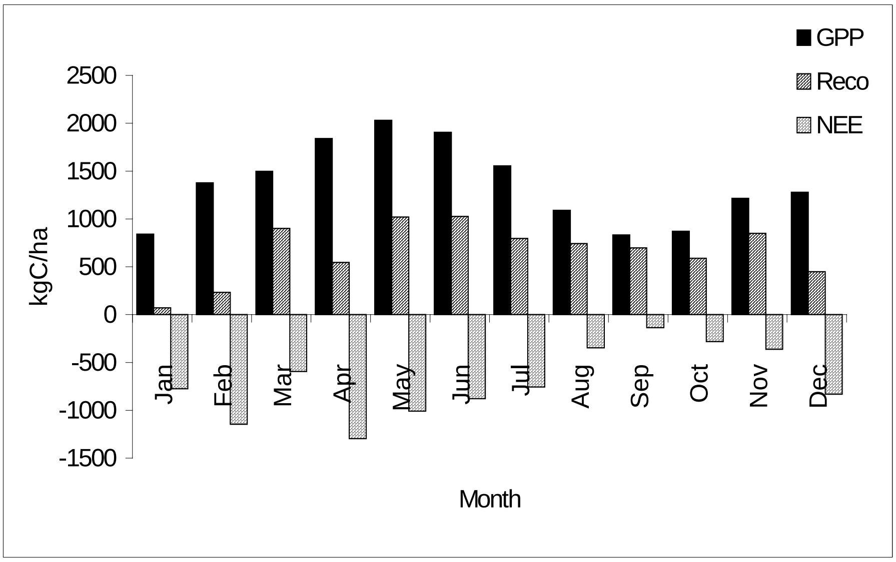

Figure 1 – 2004 monthly evolution of gross primary production (*GPP*), ecosystem respiration (R_{eco}) and net ecosystem exchange (*NEE*), obtained with the flux partitioning and gap filled with (http://gaia.agraria.unitus.it/database/eddyproc/)

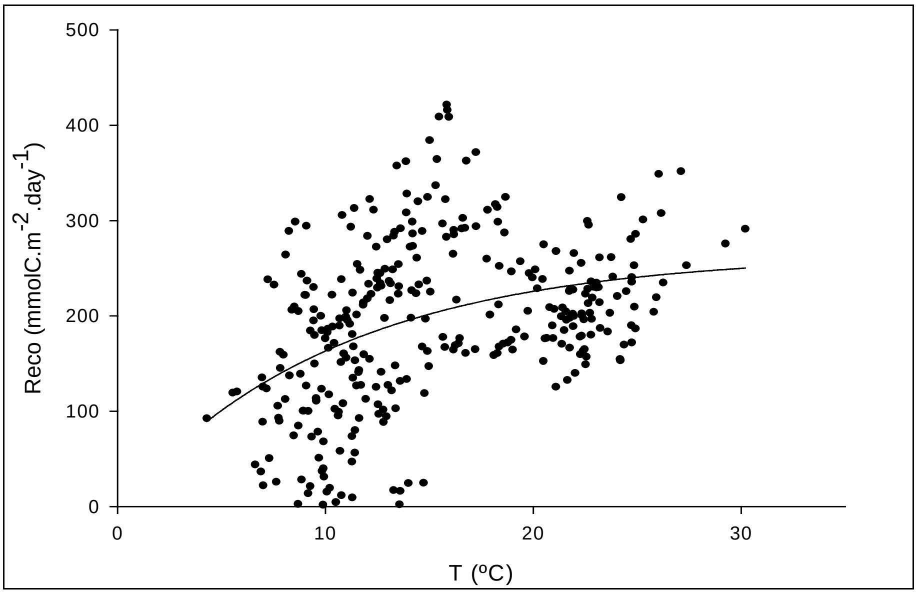

Figure 2 – Daily integrals of ecosystem respiration (Reco) versus the mean air temperature (T) for those days

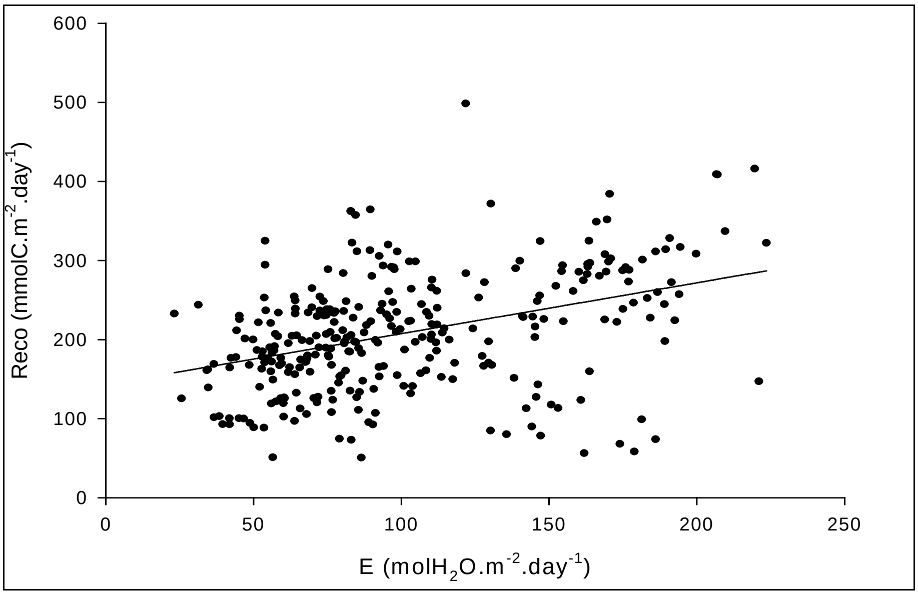

Figure 3 – Daily integrals of the ecosystem respiration (*Reco*) versus evapotranspiration (*E*)

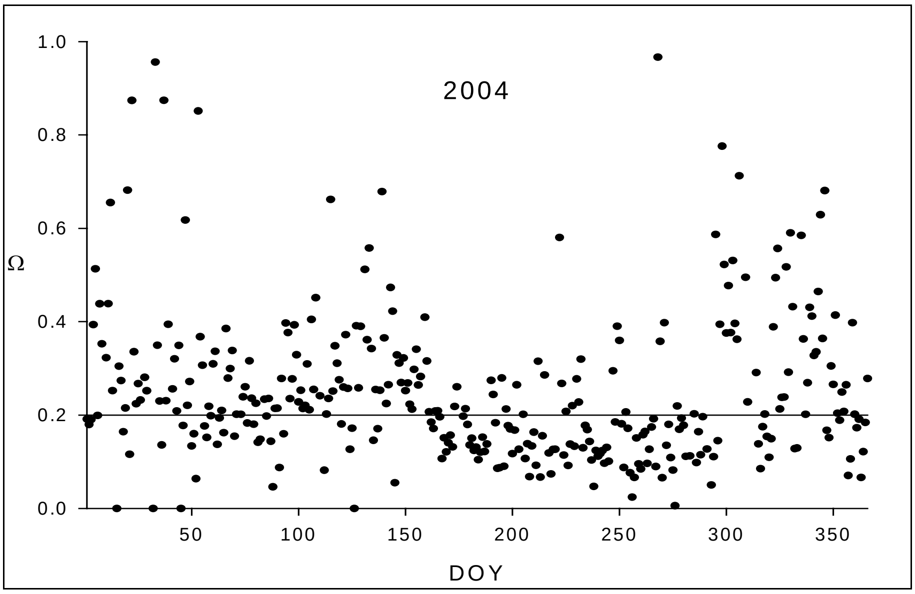

Figure 4 - 2004 evolution of the Ω (diurnal periods) coefficient

The carbon uptake maximum, -9μmol.m^{-2}.s^{-1}, is lower than the one achieved in other months (like February or May), concomitantly to the seasonal variation above mentioned. The nocturnal respiration (mean value of 3μmol.m^{-2}.s^{-1}) is higher than in May (mean night air temperature of 18ºC for August vs. 12ºC for May). This summer daily decrease of carbon uptake was also reported by RODRIGUES *et al.*, 2005, to the same site in 2002 and 2003. The evapotranspiration curve (peak value of 4mmol.m^{-2}.s^{-1}) is phased with radiation, but its values are lower than the ones obtained in May, due to less water availability, but higher than in February due to more available energy and higher *WVD*.

In February a month representative of the winter period with lower air temperatures the daily pattern of atmospheric fluxes (Figure 6) is distinct from August, showing that both the fluxes are perfectly in phase with R_g. Maximum values of atmospheric fluxes and radiation are simultaneous at noon. Peak radiation flux is of 450W.m^{-2}. Maximum carbon uptake and evapotranspiration are 15µmol.m^{-2}.s^{-1} and 2.5mmol.m^{-2}.s^{-1}. Nocturnal respiration shows very low values (mean value of 1.5µmol.m^{-2}.s^{-1}) due to low night temperatures (mean value of 8ºC). The experimental data depicted in Figure 7 and Figure 8 allow for a confirmation of Penman-Monteith equation (10) assumptions about the role of radiation and water vapour deficit in atmosphere in the control of evapotranspiration and stomatal aperture with the consequences in carbon uptake by trees. If just the days in which the *WVD* at noon is less than 1kPa, typically outside June to October (Table 1), are taken it is clear that the *NEE* is directly proportional to the global solar radiation (Figure 7). Low *WVD* is associated to stomatal opening and so the radiation control of carbon uptake is more effective.

Also it may be noticed, for summer days with WVD at noon higher than 1kPa, (Figure 8) a decreasing tendency of *NEE* as the *WVD* increases. For values of *WVD* lower than 1kPa this was not observed, meaning that the influence of *WVD* is not relevant in such conditions.

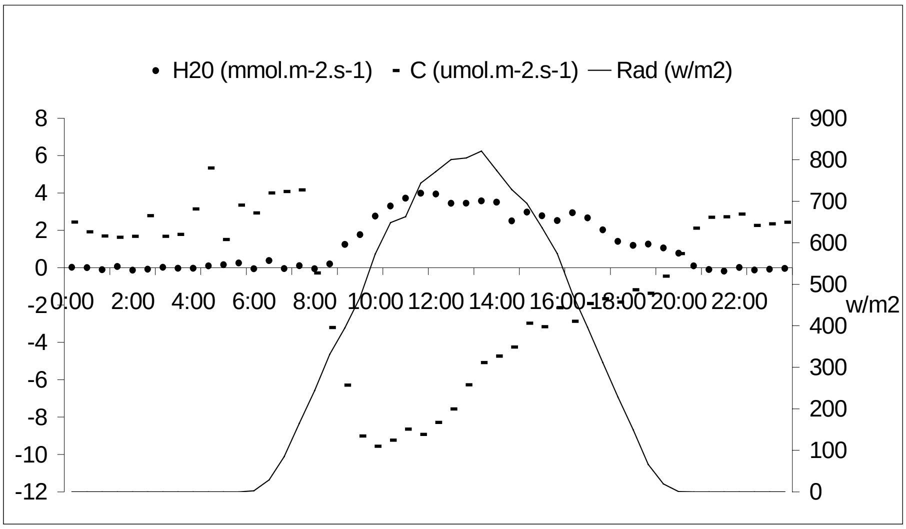

Figure 5 – Mean daily patterns, for August, of carbon (C) and water vapour (H_2O) fluxes (left *yy* axis) as well as of global solar radiation (right *yy* axis)

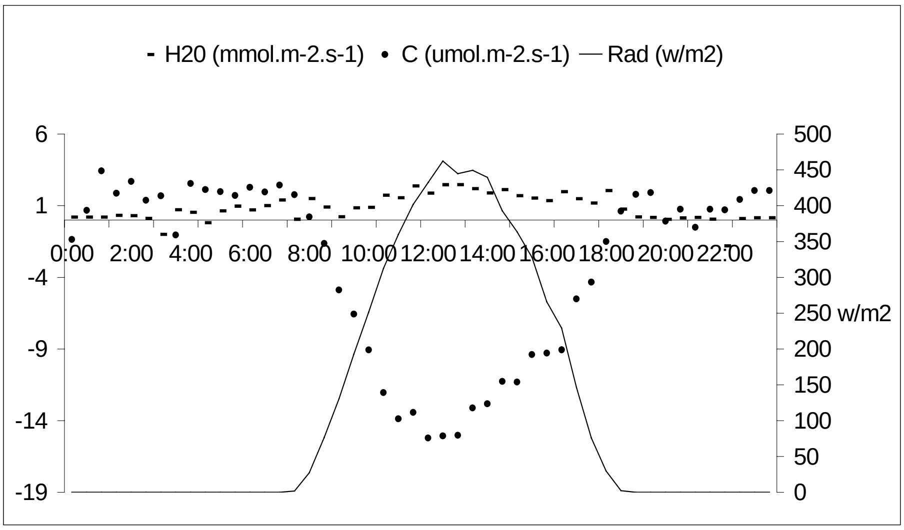

Figure 6 – Mean daily patterns, for February, of carbon (C) and water vapour (H_2O) fluxes (left *yy* axis) as well as of global solar radiation (*yy* right axis)

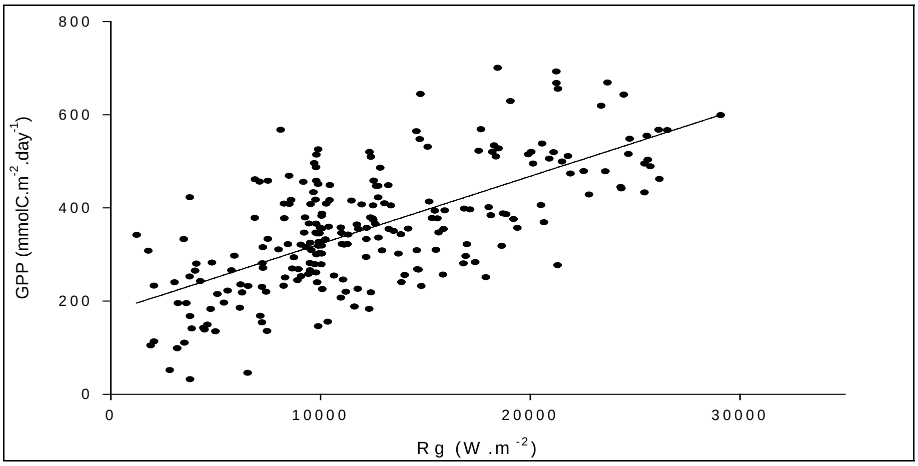

Figure 7 – Daily integrals of gross primary production (*GPP*) versus global solar radiation (R_g), considering just the days with water vapour pressure deficit (*WVD*) at noon inferior to 1 kPa

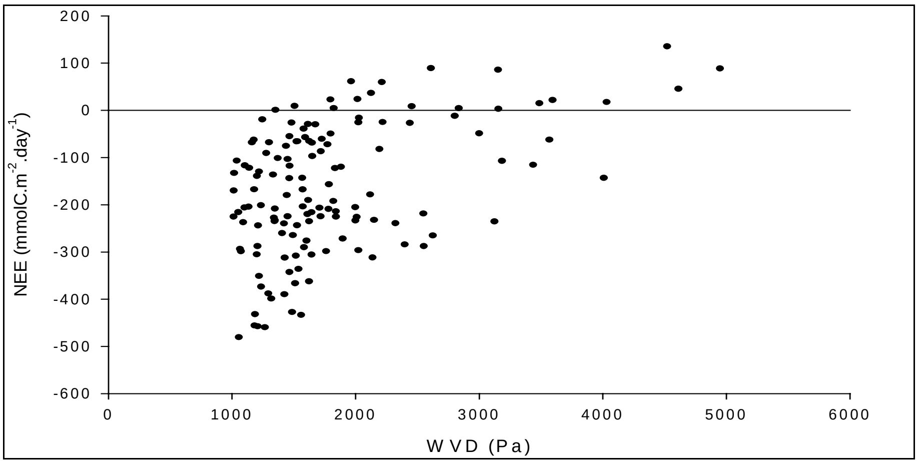

Figure 8 – Daily integrals of net ecosystem exchange (*NEE*) versus water vapour pressure deficit (*WVD*), considering just the days with *WVD* at noon higher than 1 kPa

Conclusions

The Herdade da Espirra *Eucalyptus* plantation is a strong carbon sink, with an uptake (2004) of 7.9tonC.ha^{-1}.year^{-1}. According to the values described in RODRIGUES *et al.*, 2005, this was slightly lower than the 9.3tonC.ha^{-1}.yr^{-1} obtained in 2003.

The diurnal *NEE* is mainly a function of solar radiation all year around, the two variables being perfectly in phase except from July to September. For this exception period, the maximum uptake occurs 3 hours before the peak solar radiation, and its value is lower than the one obtained for the rest of the year (-9 μ mol.m^{-2}.s^{-1} against -15 μ mol.m^{-2}.s^{-1}, respectively). After this morning maximum value there is a clear diminishing in the carbon assimilation, due to a stomatal closure, to face the high *WVD* values, and restrict water losses by trees. This reasons cause a clear inflexion in the monthly carbon uptake during summer. The evapotranspiration is clearly control-led by water vapour deficit with decoupling factors varying from 0.1 to 0.4, typically a characteristic of forest canopies. In the period from July to September evapotranspiration dependency on *WVD* increases as a conesquence of the mentioned stomatal closure.

The ecosystem respiration is limited by the short water availability, showing a pattern almost constant along the hottest months. Ecosystem respiration is thereby also affected by moisture adverse conditions and summer depression in *NEE* is mostly due to stomatal closure and carbon uptake than to increased respiration.

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