5.4 SEASONALITY AND INTER-ANNUAL FOREST ATMOSPHERE CARBON AND WATER EXCHANGES IN A PORTUGUESE EUCALYPTUS PLANTATION (MEDITERRANEAN CLIMATE)

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ABSTRACT

Eddy covariance flux data from the Portuguese CarboEurope forest site 'Herdade da Espirra' obtained from 2003 to 2005 is analysed. A 32m tower contains at its top the eddy covariance unit, as well as an automatic weather station. The site (38º38'N, 8º36'W) is an *Eucalyptus Globulus* 300 hectare plantation, 11 years aged forest with 20m mean canopy height and trees spacing 3x3m. Cover is located in flat terrain, extending for distances from 700m to 1800m in the several directions, from the measurement tower.

Within a Mediterranean climate, subjected to periodic drought, linkage between water and carbon balances is therefore a major issue.

This year-long type assimilation forest acts as a strong carbon sink reaching an uptake of -938 $gC.m^{-2}.yr^{-1}$ in 2003, year with 11% less precipitation than the 30 years mean value for the location (709mm). A depression in carbon uptake occurred during summer, due to increased stomatal resistance associated with atmospheric water vapour deficit. In 2004 the precipitation was 48% under the mean value, and although the annual carbon balance pattern was quite similar when compared with the previous year, the carbon uptake was reduced in 10%. The second consecutive dry year (2005), suffered 67% rain and 56% NEE reduction in the period between January and September relatively to the same period in 2003. The impact in the NEE was caused by a high stomatal control of the evaporatory demand, affecting negatively the carbon assimilation. The Ω values evaluated along the three years shows a pattern that confirms the prevalence of the imposed evapotranspiration, with very low values (<0.2) during 2003 and 2004 summertime and the whole 2005 (until Sept.), linked with the NEE evolution.

Water availability is clearly the key factor determining the forest-atmosphere carbon exchanges variability, either in daily, monthly and yearly time scales. GPP positively correlates with evapotranspiration (r^2=0.64), considering the monthly values. Simple linear regression between annual net carbon uptake and precipitation, although with only three years (Jan. to Sept.), shows a high positive correlation (r^2 = 0.95).

Keywords: carbon, net ecosystem exchange, evapotranspiration, Mediterranean climate, Eucalyptus forest, drought, eddy covariance.

1. INTRODUCTION

Mediterranean climates are characterized by discrete periods of intense rain events, which occur mainly from October to April. Periodically these events are less frequent and/or less intense, resulting in dry years.

During the last decades of the 20th century, Western Mediterranean regions felt increased drought frequency, due to higher air temperatures and diminished winter-spring precipitation (Miranda *et al.*, 2002).

Therefore, in these regions, the linkage between water and carbon balances of ecosystems is a major issue in any climate change study, since water will certainly be a main factor controlling plant carbon uptake.

The climate of all Portuguese territory located at South of Tejo is typically Mediterranean (Miranda *et al.*, 2002), so every ecosystem there will feel the impact of increased periods or intensities of drought.

The Portuguese Meteorological Institute (http://www.meteo.pt/) classified 2005 as an extremely dry year. In fact the same institute relates that it was the year with less rain fall since 1931, turning it in a case study for the estimation of the different impacts in the biosphere that future climate can induce in Mediterranean regions, particularly in Portugal.

Portuguese forest area covers 37% (more than 3 million hectares) of the national territory. Eucalyptus, used mainly for pulp production, were introduced more than 60 years ago, representing now 21% of forested area (700 000 ha). Values for forest and eucalyptus cover taken from "Plano de Desenvolvimento Sustentável da Floresta Portuguesa", 1998 (http://www.dgrf.min-agricultura.pt/ - Portuguese Forestry Resource Service).

The main purpose of this manuscript is, in this context, to show the impact of the 2005 drought in a plantation of a specie with high productivity, associated to high water consumption, as the eucalyptus, in terms of its carbon sequestration capacity.

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This goal is achieved thanks to the continuous measurement of carbon and water vapour fluxes by the eddy covariance method (Baldocchi, 2003; Aubinet *et al.*, 2000). The big-leaf concept was used in order to evaluate the response of the canopy to water stress.

Data from January 2003 until September 2005 is analyzed.

2. SITE DESCRIPTION AND METHODS

2.1 Site

Field measurements were carried out in a *Eucalyptus globulus* 300 hectare plantation (38º38'N, 8º36'W), part of Espirra Estate, a 1700 hectare agro-forestry area situated in the municipality of Palmela, 60 km south of Lisbon. The site is part of the CarboEurope-IP (http://www.carboeurope.org).

The 11 years aged plantation has 20m mean canopy height and trees spacing 3x3 meter. Leaf area index (LAI) values of 2.8 and 2.47 were estimated for 2003 and 2005, both in January.

The cover is located in flat terrain, extending for distances from 700m to 1800m in the several directions, from the 32m height measurement tower.

The eddy covariance unit is installed in the top of the tower (12m above canopy), and is comprised by an ultrasonic Gill anemometer R2 and an open path analyzer IRGA LI-7500. With a 20.8Hz acquisition rate, the data from this unit is stored in a computer installed in the tower.

An automatic weather station is also running; measuring incident and reflected global and photosyntheticaly active radiation (PAR) radiations, net radiation, soil temperature, air temperature at three different heights, air humidity, wind speed at four different heights and wind direction (for equipment description – Rodrigues *et al.*, 2005). Data acquisition is done with a Campbell Scientific CR10 model data logger.

2.2 Eddy Covariance – Measurement and treatment

Data for fluxes and meteorological variables consist in means over 30 minute periods, exception made for precipitation, for which the integral over the same period is the value taken in consideration.

For fluxes, the calculation of the covariance for the mentioned 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. Independent time lags for carbon dioxide and water vapour were determined, in order to maximise the covariance between vertical wind velocity and the gas analyser signals. 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).

Following the 3 flags scheme (Foken and Mauder, 2004), 0, 1 and 2 in which 0 represents data of highest quality, capable of use in fundamental research; 1 is for data for use in long term observation programs; 2 is data that should not be considered, gap filling must be done. Data that do not fulfil the requirements described in the previous paragraph is, of course, flagged 2, the rest is submitted to stationarity test and integral turbulence characteristics test (Foken and Wichura), and flagged 0 or 1 according to the results (Mauder and Foken, 2004).

In steady state test, 30 minute mean covariances between the vertical velocity component and an horizontal wind velocity, or a measured scalar (CO_2, H_2O or temperature), are compared with 6 mean values for 5 minute periods (part of the same 30 minute period); if the biggest difference is lower than 30%, the correspondent calculated flux is flagged 0 in the test, if it is between 30% and 100% is flagged 1 and if the difference is higher than 100% is flagged 2. Same scheme of differences is applied in the integral turbulence characteristics test, for the comparison between semi-empirical (function of atmospheric stability) and measured values of the quotient between standard deviation of vertical velocity, horizontal velocity and/or temperature and u_*, depending on the flux in case (vertical velocity is applied to all fluxes).

If both test result in flag 0, then the final flag is 0; if at least one result in flag 1, then the final flag is 1; finally, if at least one is flagged 2, then the final flag is 2.

The extension of the homogeneous cover is a guaranty for good fetch conditions, and the fact that it is located in a flat terrain, as well as the sensors located only 12m above canopy, surely reduces problems related to advection and night drainage. A combined footprint and flux quality analysis was performed (Göckede *et al.*, 2005) showing that the average measured flux contribution from the target forest is about 87 percent, with 99% of all measurements exciding 80% contribution from the eucalyptus. The overall flux quality was shown to be also very high, particularly for CO_2.

Net ecosystem exchange (NEE) value was taken as the sum of the CO_2 covariant flux with the storage term, calculated for one point measurement, according to Greco and Baldocchi (1996).

Gap filling of missed or inaccurate data (flag=2) of carbon and water vapour fluxes was applied, using the online software (http://gaia.agraria.unitus.it/database/eddyproc/), that combines the look up tables and mean diurnal variation methodologies. The same software allowed a partitioning of NEE in gross primary production (GPP) and ecosystem respiration (Reco), by calculation of ecosystem respiration by adjustment of Loyd-and-Taylor regression model to the night time NEE (or respiration since photosynthetic activity stops) and soil temperature (Reichstein *et al.*, 2005). GPP is then obtained as: GPP=-NEE-Reco, with NEE following the sign convention on which a negative value indicates a net carbon uptake.

2.3 Application of the big-leaf concept

In order to analyse the water availability to respond to plant physiological needs, in this case with the objective of identify the stomatal control on carbon uptake, the big-leaf approach was used.

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):

$$E = \frac{\Delta(R_n - G) + \frac{\rho c_p WVD}{r_a}}{L\left[\Delta + \frac{\gamma(r_c + r_a)}{r_a}\right]} \qquad (1)$$

In equation (1) E corresponds to the evapotranspiration, 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 $1kg.m^{-3}$; c_p is the specific heat at constant pressure of air, considered constant at $1010J.kg^{-1}.K^{-1}$; r_a is the aerodynamic resistance in $s.m^{-1}$; L is the heat of vaporization of water, assumed constant at $2465x10^3J.kg^{-1}$ (corresponding to a Temperature of 15ºC); and γ is the psychometric constant in $Pa.K^{-1}$; WVD is saturation vapour pressure (Pa). Soil heat flux was estimated from the energy balance ($G=R_n-(H+LE)$), and in this case, for the purpose in cause, it represents also the energy storage in the air beneath the tower and vegetation.

Aerodynamic resistance was calculated with equation (2), were the friction velocity (u_*) is calculated from covariant momentum flux, and u is the mean horizontal wind velocity:

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

In malfunctioning periods of the eddy covariance unit, r_a was calculated according to equation (3):

$$r_a = \frac{\left[\ln\left(\frac{z-d}{z_0}\right)\right]^2}{uk^2} \qquad (3)$$

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 (1) by McNaughton and Jarvis (1983) resulted in:

$$E = \Omega\frac{\Delta(R_n - G)}{L(\Delta+\gamma)} + (1-\Omega)\frac{WVD}{r_a + r_c} \qquad (4)$$

where Ω is the dimensionless decoupling factor. Equation (4) parts equation (1) in two components. The first term on the left side is the so called equilibrium evaporation, 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:

$$\Omega = \frac{\frac{\Delta}{\gamma}+1}{\frac{\Delta}{\gamma}+1+\frac{r_c}{r_a}} \qquad (5)$$

In equation (5) the r_c value calculated by inversion of Penman-Monteith equation, using evapotranspiration, allows the calculation of Ω.

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 (Blanken *et al.*, 1997). 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 the dynamics or stomatal opening are controlled by the interaction of long term factors, such as biogeochemical processes, associated to nutrient cycling and organic decomposition, and short term ones such as the atmospheric vapour deficit or other physiological.

In this manuscript Ω is presented with the objective of checking the main factors controlling evapotranspiration, and therefore, how can that be linked to carbon fluxes.

3. RESULTS AND DISCUSSION

Meteorological parameters, namely air temperature (T), global solar radiation (Rg) and precipitation (P) are shown in **Figure 1**, as monthly values, for the years 2003, 2004 and 2005 (the last one only until September).

Monthly temperatures are concomitant with the 30-year averages (1961-1990) for the closest meteorological station (Pegões, 38º38'N, 8º39'W). Nevertheless it is clear that 2003 was a hot year, with the mean, maximum and minimum temperatures higher than the 30-year means. Mean annual temperatures were 16.8ºC and 15.1ºC for 2003 and 2004, when compared with the long-term mean of 15.9ºC. The mean temperatures for the January-September period were 18.1ºC, 16.1ºC and 16.8ºC, respectively for 2003, 2004 and 2005; that compared with the climatological mean of 16.6ºC, reinforce the idea of the hotter 2003 and other years close to the average.

Global solar radiation was lower in 2005 (January to September), except for May and June. For the January to September period the integrals were 5189MJ.m^{-2}, 5198MJ.m^{-2} and 5489MJ.m^{-2}, respectively for 2003, 2004 and 2005, meaning about -6% for both the first years. This, of course is correlated with the abrupt diminishing in rainfall for 2005.

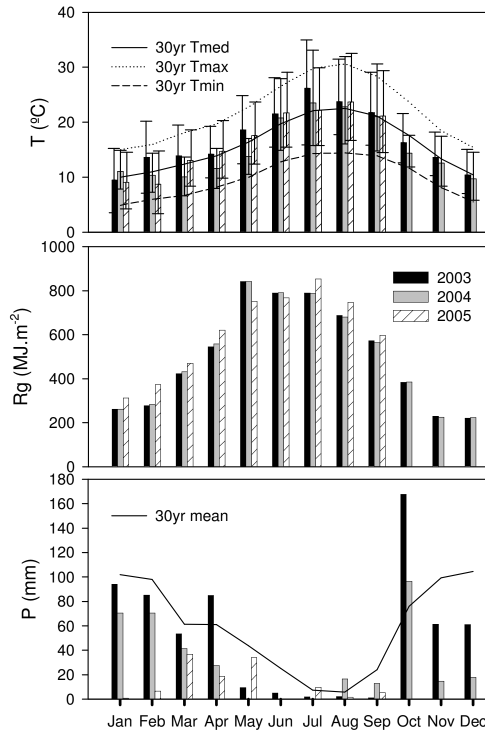

Figure 1 – From the top, bars representing monthly values of air temperature (T), corresponding to mean values for each month; global solar radiation (Rg), corresponding to total radiation in each month; and precipitation (P), corresponding to total rainfall in each month. In temperature (T) plot, vertical bars indicate the mean minimum and maximum daily temperatures for each month, the lines are 30 year mean values (1961-1990) from the nearest meteorological station (Pegões, 38º38'N, 8º39'W). The solid line is the mean air temperature for each month, the dotted line is the mean minimum temperature for each month and the dashed the mean maximum. In precipitation plot (P), the solid line is the 30-year mean value.

As referred in the introduction, 2005 was an exceptionally dry year, following two years that where also below the mean annual precipitation, as can easily be detected in the precipitation plot of **Figure 1**. The climatological mean annual value is 709mm, meaning that the reductions were of 11% for 2003 and 48% for 2004. Considering the January-September period, the reductions were 21% less for 2003, 44% and 74% for 2004 and 2005. Annual pattern in 2003 and 2004 is typically Mediterranean, with winter-spring rains and almost no precipitation in summer months.

In **Figure 2** net ecosystem exchange (NEE) and evapotranspiration (E) monthly integrals are shown. Both plots evidence that annual patterns are similar along the years. Carbon uptake increases in spring, April being the month with maximum uptake for all the years, E also increases, and then NEE shows a clear summer depression (June/July to September), that corresponds to a reduction in E, as well. This evidences 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.

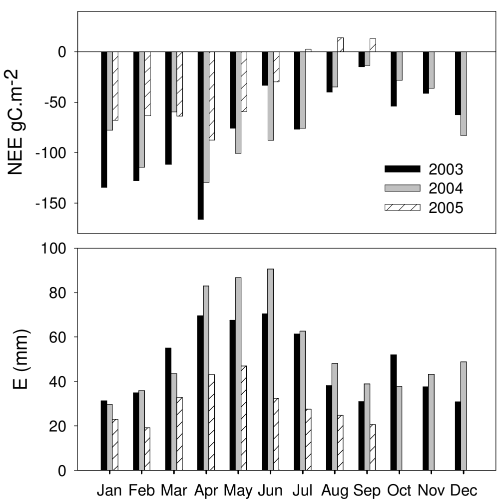

Figure 2 - Bars representing monthly values of net ecosystem exchange (NEE), and evapotranspiration (E), both corresponding to total month values.

Annual carbon uptakes were $-939gC.m^{-2}.yr^{-1}$ for 2003 and $-841gC.m^{-2}.yr^{-1}$ for 2004, indicating that in the second year a restriction in uptake was already felt. From April to June 2004, NEE and E were higher than in 2003 showing that in this period, despite the less amount of rain fall, when compared to 2003, the eucalyptus roots were able to reach deeper soil water. Analysing the period between January and September, the NEE for 2003 was $-781gC.m^{-2}.yr^{-1}$, so the reductions were 11% and 56% for the years after. For the last year, during the summer period, ecosystem respiration (Reco) is even higher than photosynthesis (GPP), shown by the NEE positive values.

The NEE partitioning in GPP and Reco (data not showed – Mateus *et. al.*, 2005) demonstrates that NEE reduction during hotter months is determined mainly by GPP decrease. Ecosystem respiration for all years does not vary that much from March to November. The lack of water also affects respiration, in the sense that it cannot respond as positively as it would to soil temperature increase.

In **Figure 3** is shown the seasonal variation of Ω values for the tree years. In the first two years it is clear that for the same period of the NEE depression Ω values go below a threshold of 0.2, indicating that in these months the lowering of evapotranspiration is related to increased stomatal resistance to face the high water vapour deficit values, in a period when water availability is not so high.

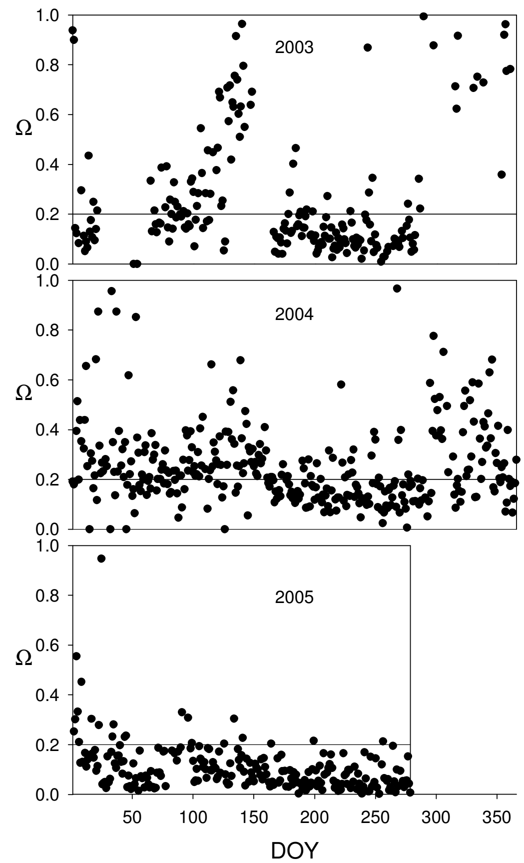

Figure 3 – Decoupling factor (Ω) seasonality, for the years 2003, 2004 and 2005, the latest only until DOY 273 (30th September). Values shown obtained at midday.

Plotting GPP against E (monthly values), **Figure 4**, shows a positive correlation (r^2=0.64). It confirms that the stomatal control to reduce water loss by the canopy is a main factor controlling carbon fluxes (reducing uptake). Net ecosystem exchange leads to a poorer correlation, since Reco produces more variability.

In **Figure 5** Rg and NEE mean diurnal variations for April and September 2005 are shown. These months were the chosen ones because they correspond to maximum and minimum NEE, respectively. The fact that both months present similar radiation availability ($620MJ.m^{-2}.month^{-1}$ for April and $597MJ.m^{-2}.month^{-1}$ for September, 2005) is also a particularity contributing for the explanation of the different patterns, by water availability and evaporatory demands.

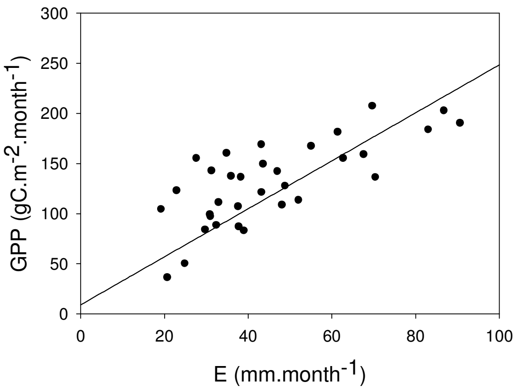

Figure 4 – Relationship between monthly (2003, 2004 and 2005 months, the last only until september) total gross primary production (GPP) and monthly total evapotranspiration (E). The regression line is GPP=9.12+2.39E, and r^2=0.64.

In April NEE is in phase with incident radiation, reaching a maximum at about midday, of -12μmolC.$m^{-2}.s^{-1}$ (mean value). September maximum NEE is at approximately half past nine, -3.3μmolC.$m^{-2}.s^{-1}$, followed by a clear reduction, with the ecosystem presenting a respiration higher than uptake in the afternoon. This asymmetric diurnal pattern is clearly due to stomatal closure as temperature increases (increasing also water vapour deficit) to control transpiration rates. Respiration is also lower in September (as showed by the night values), since it is also affected by less soil water availability.

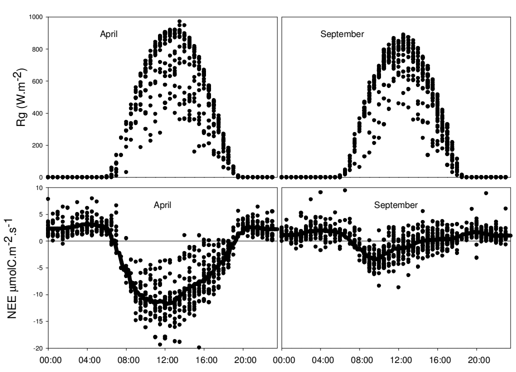

Figure 5 – Mean diurnal variations for global solar radiation (Rg) and net ecosystem exchange (NEE) for April (left graphs) and September (right graphs) months (year 2005). Dots represent measured mean values for the 30 min periods, only the ones with highest quality (flag=0) in the case of NEE. The lines in the NEE graphs are running averages of the plotted data.

The fact that NEE was lower in 2005, does not mean that diurnal patterns were different relatively to other years. What changes significantly is the amplitude of the gas exchange, not its pattern. In **Figure 6** it is showed how the amplitude is reduced as an impact of drought, plotting NEE as a function of Rg. The rectangular hyperboles fitted equations, as well as the correlation coefficients are in **Table 1**. It is clear that in 2003 the response from NEE to radiation is higher, and the maximum uptake is also bigger, than in 2004. The same happens to 2004 comparatively to 2005. Respiration (hyperboles Y-axis interception) also lowers in the same sequence (2003 to 2005).

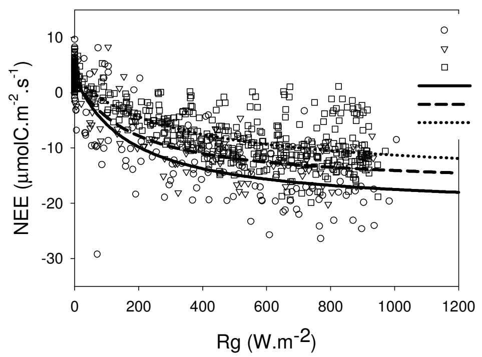

Figure 6 – Net ecosystem exchange (NEE) as a function of global solar radiation (Rg), for April (month with maximum annual carbon uptake) in 2003, 2004 and 2005. Only the NEE values with highest quality (flag=0) were used. The rectangular hyperboles fitted equations are presented in Table 1.

2003: $$\mathrm{NEE} = 3.06 - \frac{24.14\mathrm{Rg}}{175.29 + \mathrm{Rg}}$$; r^2=0.75

2004: $$\mathrm{NEE} = 2.77 - \frac{19.78\mathrm{Rg}}{173.97 + \mathrm{Rg}}$$; r^2=0.79

2005: $$\mathrm{NEE} = 2.66 - \frac{18.46\mathrm{Rg}}{323.12 + \mathrm{Rg}}$$; r^2=0.75

Table 1 – Rectangular hyperboles fitted for April 2003, 2004 and 2005. NEE -μmolC.$m^{-2}.s^{-1}$; Rg- W.m^{-2}

The impact of drought in carbon sequestration in an annual basis can be resumed in the positive liner correlation NEE=-1.65P-251 with NEE in gC.$m^{-2}.yr^{-1}$ and P in mm.yr^{-1} (r^2=0.95), from the period between January and September. Despite the fact that it is a regression made with only 3 points (years 2003, 2004 and 2005), together with the anterior information presented, it is clear that there is a tendency. Notice that, at such time scale, Reco variability is smoothed.

4. CONCLUSIONS

Linkage between forest-atmosphere carbon and water exchanges is a main issue in Mediterranean areas. Both are closely linked, by the stomatal control of tree transpiration to reduce water loss during dry hot summer months.

The eucalyptus plantation, having a yearlong type assimilation pattern, acts as a strong carbon sink, with NEE of $-939 gC.m^{-2}.yr^{-1}$ in a regular year (2003). In such a year maximum uptake occurs in beginning of spring (April), followed by a summer depression (June/July to September), period of stomatal closure. This pattern is perfectly phased with the Ω factor, also reduced in summer, showing values below a threshold of 0.2.

In this ecosystem drought had a major impact in carbon assimilation. The year 2005 was the one with less rainfall since 1931, so it felt a NEE reduction of 56% (January to September), when compared to 2003. The annual pattern is maintained, but monthly values magnitude is reduced. Positive monthly NEE values in summer period indicate that Reco is higher than GPP.

Water availability is clearly the key factor determining the forest-atmosphere carbon exchanges variability, either in daily, monthly and yearly time scales.

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