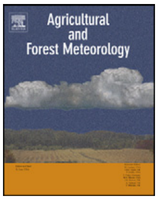
Agricultural and Forest Meteorology 151 (2011) 493–507

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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



Eight years of continuous carbon fluxes measurements in a Portuguese eucalypt stand under two main events: Drought and felling

Abel Rodrigues[a], Gabriel Pita[b], João Mateus[b], Cathy Kurz-Besson[c], Miguel Casquilho[d,*], Sofia Cerasoli[e], Alberto Gomes[a], João Pereira[e]

[a] Unidade de Silvicultura e Produtos Florestais (Unit of Silviculture and Forest Products), INRB (IP), Ave. da República, Quinta do Marquês, 2780-159 Oeiras, Portugal
[b] Instituto Superior Técnico (Technical University of Lisbon), Ave. Rovisco Pais, IST, 1049-001 Lisboa, Portugal
[c] Instituto Dom Luís (CGUL), Faculdade de Ciências (University of Lisbon), Edifício C8, Campo Grande, 1749-016 Lisboa, Portugal
[d] Centro de Processos Químicos, Instituto Superior Técnico (Technical University of Lisbon), Ave. Rovisco Pais, IST, 1049-001 Lisboa, Portugal
[e] Instituto Superior de Agronomia (Technical University of Lisbon), Tapada da Ajuda, 1349-017 Lisboa, Portugal

ARTICLE INFO

Article history:
Received 27 July 2010
Received in revised form
15 December 2010
Accepted 16 December 2010

Keywords:
Eddy covariance
Carbon
Tree felling
Water stress
Drought
GEEs

ABSTRACT

This paper reports on results from eddy covariance measurements of carbon uptake and evapotranspiration in the eucalypt site of Espirra in Southern Portugal (38°38′N, 8°36′W). This site was included in the "Carboeurope" European network and is part of a 300 ha eucalypt forest, with about 1100 trees ha^{-1}, intensively managed as a coppice for pulp production and characterized by a 12-month annual growing period. The climate is of Mediterranean type with a long term (1961–1990) annual average precipitation of 709 mm and an annual average air temperature of 15.90 °C. During the measurement period (2002–2009) two main events took place, which changed the annual sink pattern of the forest: a drought period of two years (2004–2005) and a tree felling (October and November 2006). We analyzed the daily, seasonal and inter-annual variation of carbon uptake and evapotranspiration, and their relationships with the events and the variability of the main meteorological variables. Before the felling, annual net ecosystem exchange (NEE) increased from −865.56 g C m^{-2} in 2002 to −356.64 g C m^{-2} in 2005 together with a deep decrease in rainfall from 748 mm in 2002 to 378.58 mm and 396.64 mm in 2004 and 2005, respectively. For the same period, seasonal patterns of carbon uptake showed maximum values in April and decreased in July–August. The eucalypt stand recovered its carbon sink ability since June 2007 and had a NEE of −209.01 g C m^{-2} in 2009. After the felling, the carbon uptake occurred from mid-February to mid-October, following an almost opposite pattern than that of the trees in the term of their productive cycle. A quantitative approach using generalized estimating equations (GEEs) was made for the period before the felling to relate monthly NEE and GPP with accumulated photosynthetic active radiation, water vapour pressure and precipitation. In conclusion, our study showed the relevant effects of water stress and anthropogenic interventions in the daily, seasonal and annual patterns of carbon uptake, under a context of good environmental conditions for carbon sequestration.

1. Introduction

In the present context of climate change, studies on the role of forest stands in carbon sequestration have been reported since the 1990s. These studies, relying on direct atmospheric carbon flux measurements by the eddy covariance method (Aubinet et al., 2000; Baldocchi, 2003), were supported by research programs such as Carboeurope, or global science networks such as Fluxnet. The results provided by these researches allowed an improvement of knowledge of factors explaining the seasonal and inter-annual variability of the carbon balance components. Relevant knowledge was acquired about the variability of carbon uptake with latitude and season of the year (Falge et al., 2002). Carbon uptake (NEE) and assimilation (GPP) in forest ecosystems is associated to factors related to plant biology and physical environment such as: temporal variation of meteorological conditions, leaf area index (LAI), physiological activity, length of growing season, and soil temperature and moisture content. These factors affect the carbon balance components differently (Schmid et al., 2000). While gross primary productivity (GPP) is mainly dependent on intercepted solar radiation (a function of the photon flux of photosynthetic active radiation, PAR, and LAI), total ecosystem respiration (TER) responds mostly to air and soil temperature (Carrara et al., 2004; Baldocchi, 1997; Reichstein et al., 2002). The contribution of total ecosystem respiration in European forest stands to annual NEE differences increases with latitude (Valentini et al., 2000).

---

[*] Corresponding author. Tel.: +351 21 841 7310; fax: +351 66 91 919 2021.
E-mail address: mcasquilho@ist.utl.pt (M. Casquilho).

0168-1923/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.agrformet.2010.12.007

Table 1
Annual and three-month sums of NEE, GPP and TER. Also shown are mean air temperature T_a, cumulative global radiation, R_g, precipitation, *Prec* (mm), and evapotranspiration E (mm).

Annual	T_a (°C)	R_g (MJ m^{-2})	*Prec* (mm)	NEE (gC m^{-2})	GPP (gC m^{-2})	TER (gC m^{-2})	E (mm)
2002	15.30	6007.81	748.29	−865.56	2206.04	1340.47	474.87
2003	16.06	6021.75	706.58	−791.33	1995.35	1204.02	590.20
2004	16.15	6225.97	378.58	−724.24	1834.88	1110.64	722.55
2005	16.01	6377.06	396.64	−356.64	1255.11	899.41	391.64
2006	16.51	6053.91	805.92	−619.07	1816.66	1197.91	756.40
2007	15.95	6372.38	443.05	−11.06	939.44	928.07	654.06
2008	15.86	6064.92	508.81	−200.73	1226.00	1024.97	726.73
2009	17.58	6278.04	569.53	−209.01	1294.05	1086.43	533.37
Mean	16.17	6175.23	569.68	−472.205	1570.94	1098.99	606.23
January–March							
2002	11.30	1064.70	196.25	−166.87	449.47	282.29	97.42
2003	10.56	961.90	241.07	−339.28	480.68	339.28	109.08
2004	11.41	987.80	210.03	−181.12	441.08	259.96	111.68
2005	10.22	1154.19	49.81	−190.29	372.44	182.46	84.28
2006	10.50	1002.49	206.23	−155.17	398.07	242.90	130.86
2007	11.56	1101.86	157.47	101.41	134.70	236.11	90.96
2008	12.75	1059.18	165.56	−13.33	202.95	189.62	120.10
2009	11.80	1137.99	189.90	42.42	155.10	197.71	83.82
Mean	11.26	1058.76	177.04	−112.78	329.31	241.29	103.53
April–June							
2002	15.73	2143.22	74.36	−286.53	648.71	361.87	167.89
2003	18.01	2176.96	116.10	−239.94	658.58	141.71	228.12
2004	17.76	2185.15	9.82	−297.46	649.19	351.73	294.84
2005	18.00	2138.32	52.70	−160.85	436.81	276.27	145.89
2006	18.30	2081.55	74.40	−292.00	669.03	377.03	279.41
2007	16.82	2067.08	113.86	35.82	211.69	247.81	198.28
2008	17.32	1951.30	200.61	−55.04	380.0	325.27	267.49
2009	17.42	2027.45	71.03	−140.82	374.55	233.73	169.23
Mean	17.42	2096.38	89.11	−179.60	481.33	289.43	218.89
July–September							
2002	20.66	2056.66	92.23	−97.05	380.1	283.05	85.01
2003	22.23	2049.84	39.58	−122.23	483.61	361.07	144.27
2004	22.54	2125.24	29.33	−133.49	395.03	261.54	180.19
2005	22.31	2196.61	15.63	21.76	169.66	191.42	88.29
2006	22.60	2123.97	76.16	−97.21	448.56	351.35	209.64
2007	21.30	2171.66	75.27	−82.59	312.51	229.61	241.04
2008	20.67	2123.33	21.69	−113.78	384.51	270.43	227.98
2009	25.78	2210.93	2.50	−183.30	461.50	278.10	168.60
Mean	22.26	2132.28	44.05	−100.98	379.44	278.32	168.13
October–December							
2002	13.49	743.23	385.45	−315.11	727.76	413.26	124.56
2003	13.42	833.05	309.83	−89.88	372.48	282.60	108.74
2004	12.91	927.78	129.40	−112.17	349.58	237.41	135.83
2005	13.50	887.94	278.50	−27.26	276.20	249.26	73.18
2006	14.65	845.90	449.13	−74.69	301.00	226.63	136.49
2007	14.11	1031.78	96.45	−65.70	280.54	214.54	123.78
2008	12.72	931.11	120.95	−18.58	258.53	239.65	111.16
2009	15.31	901.67	306.10	72.69	302.90	376.89	111.72
Mean	13.76	887.81	259.48	−78.84	358.62	280.03	115.68

One of the features of the present climate change is an increase in weather variability. Since the 1970s, the frequency and severity of droughts increased in the Western Mediterranean region due to higher air temperatures and diminished winter–spring precipitation (Miranda et al., 2002). As water shortages generally decrease both GPP and carbon uptake in forests (Ciais et al., 2005; Granier et al., 2007; Pereira et al., 2007), drought has a strong relevance to determine the inter-annual and seasonal variation in ecosystem carbon exchange with the atmosphere. Indeed, water stress in these regions is a major factor controlling plant carbon uptake, due to stomatal limitation of photosynthesis (Farquhar and Sharkey, 1982) and atmospheric evaporative demand. Discussion about water stress influence on leaf and canopy gas exchange is provided in multiple references, e.g. by Tenhunen et al. (1985) and Pereira et al. (1986), in Portuguese *Quercus coccifera* and *Eucalyptus globulus* stands by Lebaube et al. (2000) and Granier et al. (2008), in a French beech forest or McCaughey et al. (2006), in mixed wood forest in Canada. Other natural or anthropogenic disturbances, such as defoliation or tree felling, also contribute to determine the amounts and the time patterns of carbon fluxes by forests (Jiang et al., 2002; Xiao et al., 2003).

This paper describes the evolution of NEE, GPP, TER and evapotranspiration (E) regime in an eucalypt stand at Herdade da Espirra, at Pegões, southern Portugal, included in the Carboeurope consortium, during the period 2002–2009. Eucalypt (*Eucalyptus globulus* Labill.) forest plantations intensively managed for pulp production are highly productive with 16 m^3 ha^{-1} year^{-1} of round-wood in a 12-month growing period and cover about 19% of Portuguese forest area (647 ha). Worldwide, intensively managed plantations, providing biomass for energy and industry, correspond to about 17 (25 million ha) of plantation forests (FAO, 2010), and their expansion launched a debate about their environmental impact (Canadell and Raupach, 2008; Markewitz, 2006; Paquette and Messier, 2010; Rotenberg and Yakir, 2010).

The consideration of forest management used and the weather pattern allowed us to consider two interesting events which affected the experimental site: a two-year drought in 2004 and 2005 and a tree felling in October 2006. After the felling young

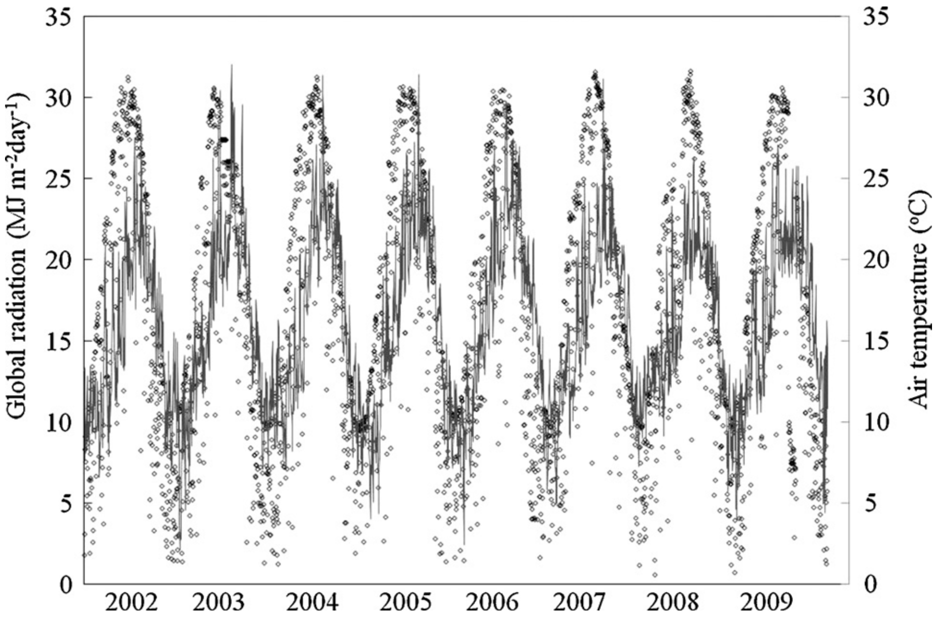


Fig. 1. Time course of daily average global radiation (◊) and air temperature (—) for the whole period (2002–2009).

sprouts underwent a thinning of three shoots out of four per stump in October and November 2008 and suffered as well leaf frost damage in winter 2007, 2008 and. In the aforementioned context, the main objectives were: (i) analysis of the impact of drought and felling in temporal patterns of carbon uptake, energy partition in the ecosystem and decoupling coefficient, (ii) the derivation of relationships between NEE and GPP and meteorological variables, and (iii) the analysis of the evapotranspiration regime and coupling coefficient by the Penman–Monteith big leaf analysis. The importance of the present work is corroborated by the fact that there are not many studies on atmospheric carbon exchanges, under severe drought conditions and anthropogenic disturbances, in this type of ecosystems.

2. Materials and methods

2.1. Site description

This study was part of the Carboeuroflux (2000–2003) and Carboeurope (2004–2008) projects. The experimental site is located in a 300 hectare eucalypt (*Eucalyptus globulus* Labill.) plantation (38°38′N, 8°36′W), extending from 700 m to 1800 m asl, part of Espirra Estate, and managed as a coppice. The site is located on a flat terrain, and the soil is a Dystric Cambisol with a mean depth of 1.3 m. Climate is of Mediterranean type with a long term average (1961–1990) precipitation of 709 mm and a mean annual temperature of 15.9 °C. Trees were planted in 1986, with a distance of 3 m, following a twelve year rotation plan after a first nine year productive cycle. In October 2006, in the end of the second rotation, a felling was made to the 12 year trees of a 20 m height average. After felling, coppice sprouting regenerated the canopy. The new stems reached 7 m height in October 2009. In winter periods of and after 2007 air temperature fell below 0 °C, and the young juvenile leaves were severely damaged by frost. A thinning of sprouts was made in October and November 2008 to remove 3 shoots out of 4 in each stump.

2.2. Instrumentation and calculations

The eddy covariance unit was installed at the top of a 33 m tower (13 m above canopy), and is comprised of an ultrasonic Gill, R2 anemometer and an open path IRGA LI-7500 analyzer with a 21 Hz acquisition rate. Subsequently, after the felling, the eddy covariance unit was moved to a height of 12 m above the ground. The distance from the tower to the edge of the stand varied between 700 m and 1800 m. Calibration of the gas analyzer with a reference gas was carried out annually. Measurements of eddy fluxes in the constant flux layer were made since January 2002. Data for fluxes consisted in averages over 30 min periods. Half hour fluxes calculation involved

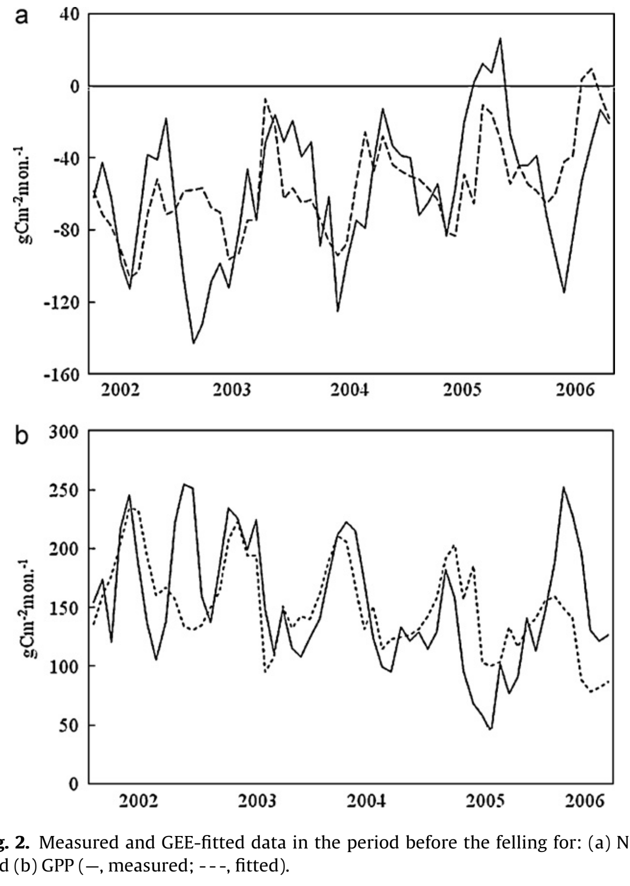


Fig. 2. Measured and GEE-fitted data in the period before the felling for: (a) NEE and (b) GPP (—, measured; - - -, fitted).

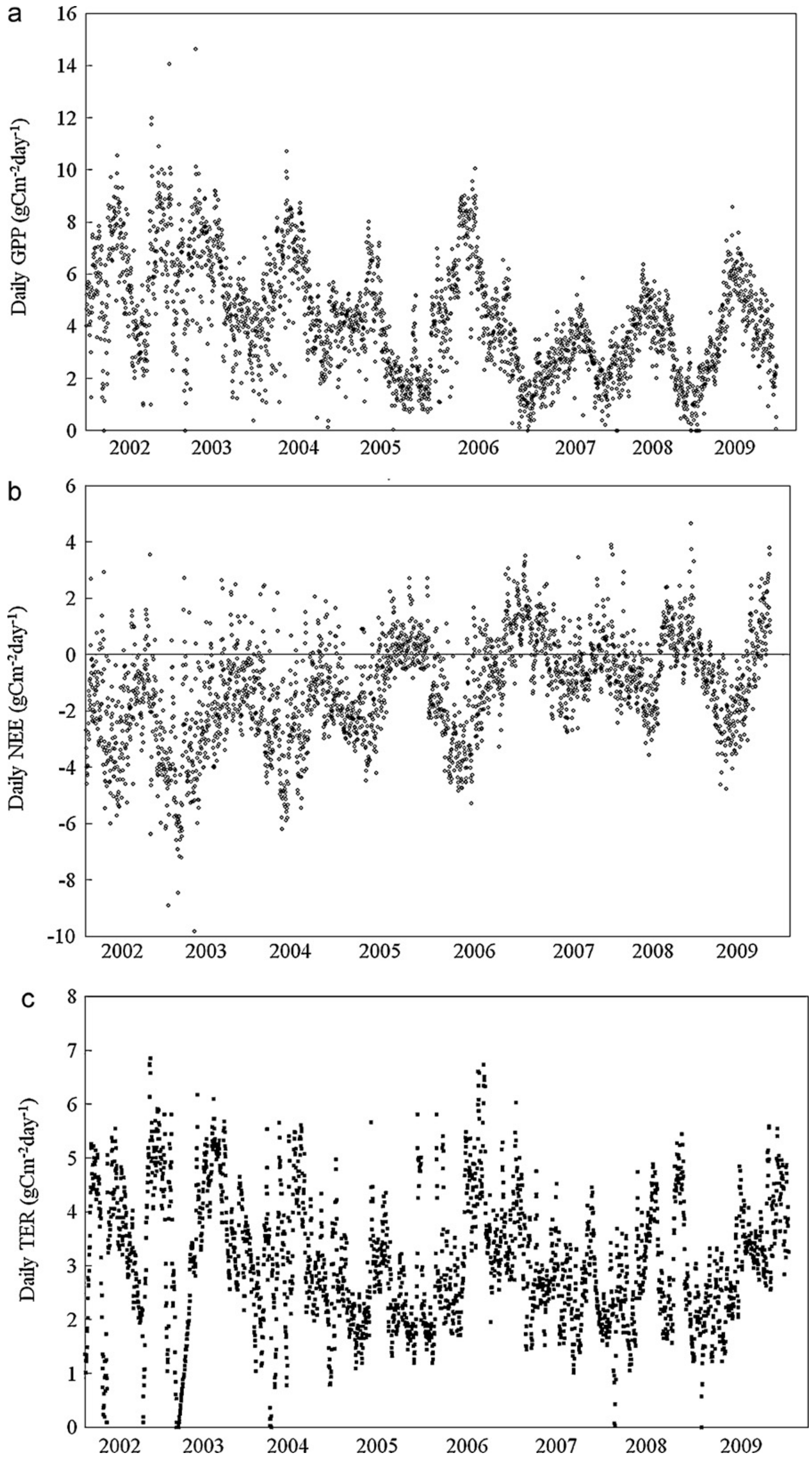


Fig. 3. Time course of daily average for atmospheric carbon in the whole period: (a) GPP; (b) NEE; (c) TER.

two axis coordinate rotation, linear detrending by least squares regression (Gash and Culf, 1996), Webb-Leuning (Webb et al., 1980) correction for density fluctuations and Schotanus correction for sonic temperature (Schotanus et al., 1983).

Meteorological data were sampled every 30 s with an automatic weather station (Campbell Scientific CR10 data logger) and averaged over 30 min periods. Precipitation was calculated using the integral of half hour periods data. Mean air temperature was measured at 25.2 m, 26.7 m, 29.2 m and 31.6 m with self produced Cu-Cons thermocouples of 0.15 mm diameter. The wind velocity was measured at the same heights as air temperature with cup anemometers (Vector Instruments, A110R), and wind direction was measured at the top of the tower with wind vane of the same brand, model W200P. Air humidity, incident solar radiation (Kipp &

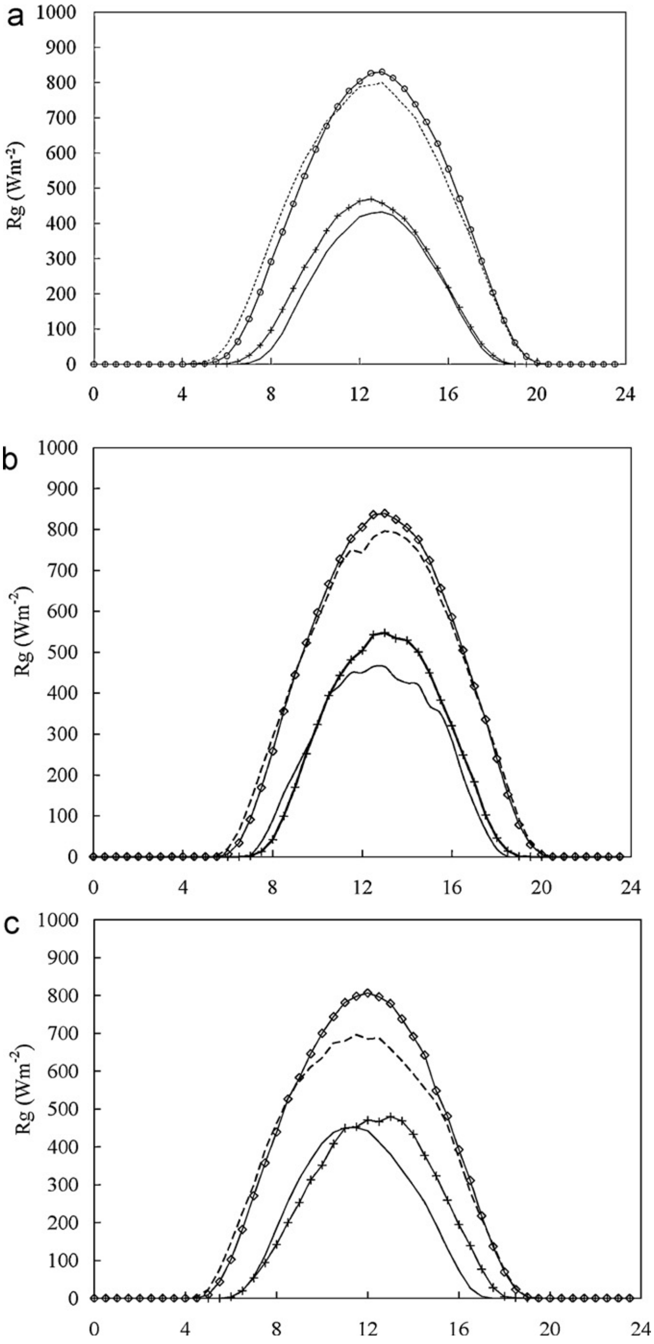


Fig. 4. Averages of R_g for typical day: (a) 2002–03; (b) 2005; (c) 2008–09 (+, January–March; - - -, April–June, ◊, July–September; —, October–December).

Zonen, model CM 6B), photosynthetic active radiation (PAR) (SKYE Instruments, model SKE510), and net radiation (Campbell Scientific, model Q6) were also measured at the top of the tower. Soil moisture data were continuously recorded with a probe Delta-T, Model PR2 every 2 h since January 2007 at depths 10 cm, 20 cm, 30 cm, 40 cm, 60 cm and 1 m. For additional equipment descriptions refer to Rodrigues et al. (2005).

The flux related to storage change of carbon dioxide in the layer below the location of the eddy covariance system was calculated by the concentration measurement of CO_2 at 33 m following the approach of Greco and Baldocchi (1996), and added to the measured covariant flux. The extension of the homogeneous cover over the flat terrain is a guarantee for good fetch.

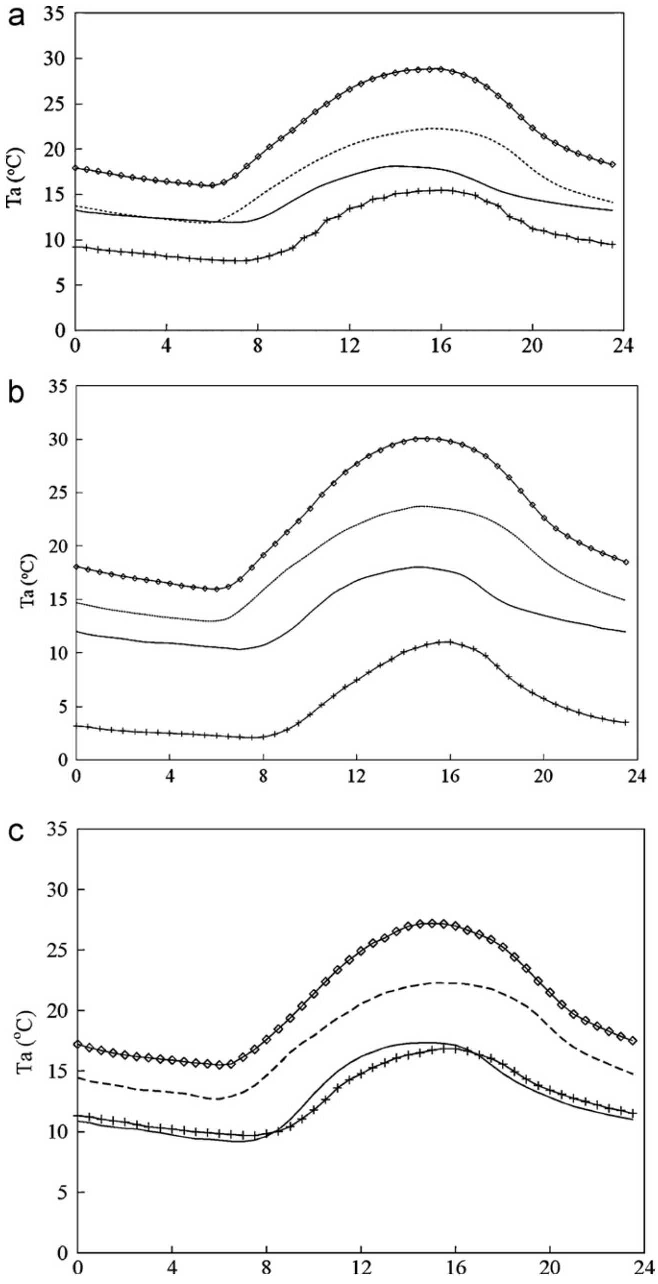


Fig. 5. Averages of T_a for typical day: (a) 2002–03; (b) 2005; (c) 2008–09 (+, January–March; - - -, April–June, ◊, July–September; —, October–December).

An integrated analysis for the period from 6 July to 29 November 2004 based on climatologic footprint analysis showed that a major contribution of 87% to the site's atmospheric fluxes was due to the eucalypt forest (Göckede et al., 2005) with 97.6% of all fluxes exceeding the threshold of 80% contribution from the target land cover (Göckede et al., 2008). Possible underestimation of carbon fluxes motivated by the Licor 7500 open path analyzer heating effect (Burba et al., 2008) were considered negligible because air temperature rarely dropped below freezing and carbon fluxes were mostly large throughout the years.

The reported carbon fluxes were submitted to quality control procedures based on the three-flag scheme presented by Mauder and Foken (2004). After the calculation of the mean half hour fluctuations covariances, a filtering removed data fluxes corresponding to (i) deviations of mean vertical velocity from zero greater than 0.35 m s^{-1}, (ii) high frequency spikes affecting single instantaneous

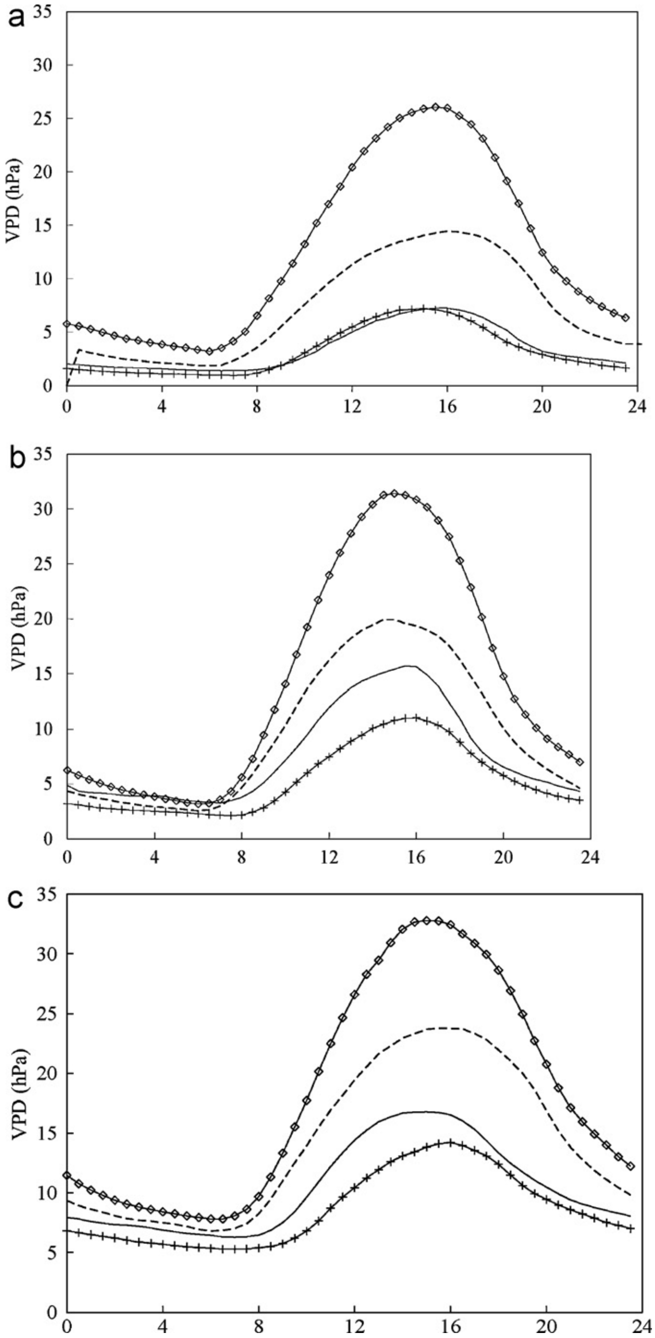


Fig. 6. Averages of VPD for typical day: (a) 2002–03; (b) 2005; (c) 2008–09 (+, January–March; - - -, April–June, ◊, July–September; —, October–December).

measurements in a percentage above 1%, (iii) the existence of occasional spikes in the half hourly flux data, using the median of the absolute deviation about the median described by Papale et al. (2006) and (iv) a friction velocity below the threshold of 0.2 m s^{-1} (Mateus et al., 2006). Flux data remaining after this filtering process were submitted to stationarity and integral turbulence characteristics. The average percentages of half hour data accepted for gap filling were 55% for carbon flux (77% at day and 33% at night) and 69% for latent heat flux (83% at day and 55% at night).

Gap filling and NEE partitioning in GPP and TER were made using the online software Eddyproc (2010) (http://gaia.agraria.unitus.it/.database/eddyproc/EddyInputForm.html) according to the methodology proposed by Reichstein et al. (2005).

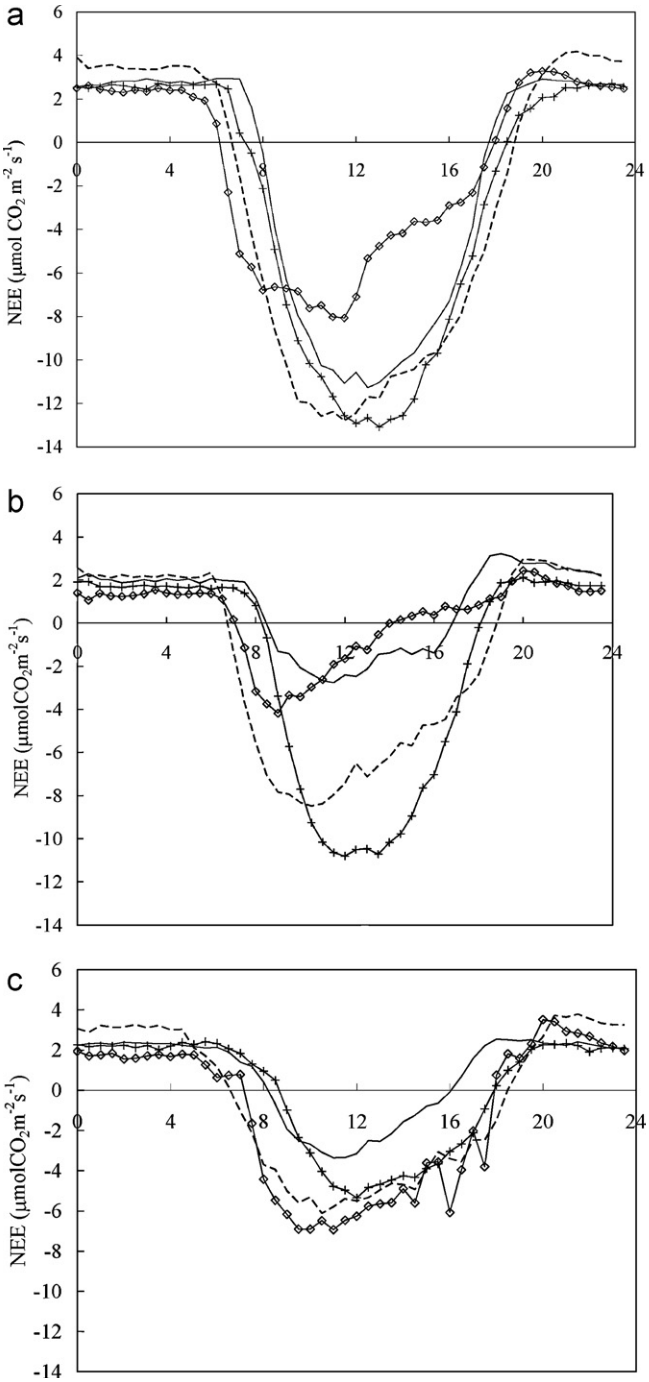


Fig. 7. Averages of NEE for typical day: (a) 2002–03; (b) 2005; (c) 2008–09 (+, January–March; - - -, April–June, ◊, July–September; —, October–December).

The analysis of the evapotranspiration regime was made by the evaluation of the decoupling coefficient Ω calculated as (Monteith and Unsworth, 1990):

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

with r_a being the aerodynamic resistance (s m^{-1}), r_c the canopy resistance (s m^{-1}), and Δ the rate of change of saturation vapour pressure with air temperature (Pa K^{-1}). The Ω coefficient is thus associated to canopy resistance and stomatal dynamics controlling water vapour and carbon dioxide fluxes. Typical values of decou-

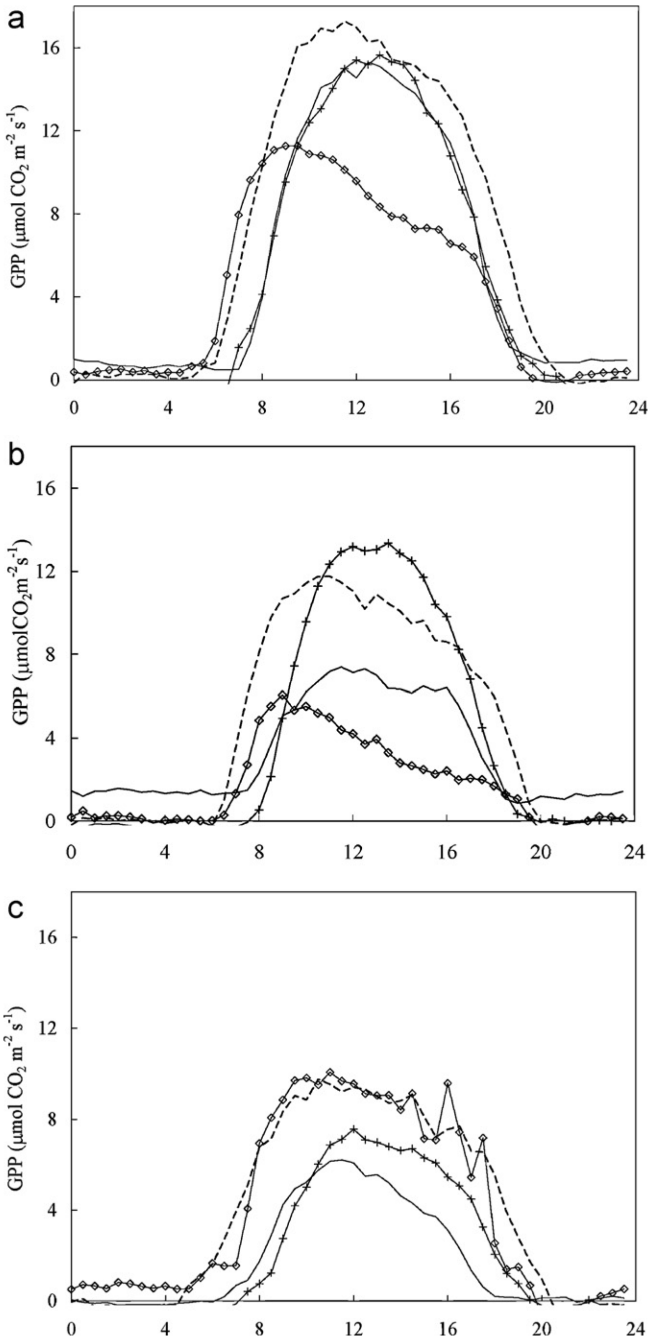


Fig. 8. Averages of GPP for typical day: (a) 2002–03; (b) 2005; (c) 2008–09 (+, January–March; - - -, April–June, ◇, July–September; —, October–December).

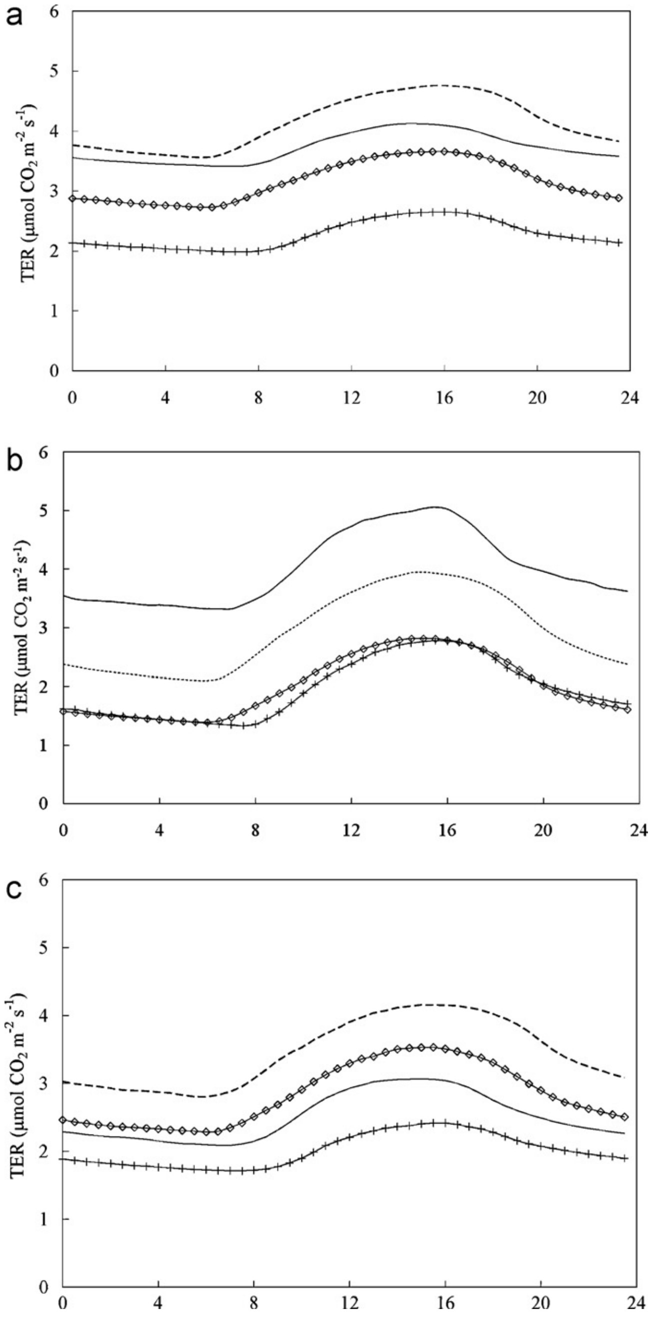


Fig. 9. Averages of TER for typical day: (a) 2002–03; (b) 2005; (c) 2008–09 (+, January–March; - - -, April–June, ◇, July–September; —, October–December).

pling coefficient are of the order of 0.1–0.2 for forest with strong coupling to the prevailing weather, contrasting to 0.8–0.9 under opposite conditions.

Aerodynamic resistance r_a is given by (Monteith and Unsworth, 1990):

$$r_a = \frac{u}{u_*^2} \tag{2}$$

where u is the mean horizontal wind velocity (m s^{-1}) and u_* is the friction velocity (m s^{-1}).

Canopy resistance, r_c, was obtained inverting the Penman–Monteith equation (Monteith and Unsworth, 1990) using latent heat flux, LE, obtained by eddy covariance,

$$r_c = r_a \left(\left\{ \frac{\Delta (R_n - G) + \rho c_P \left[e_S(T_a) - e \right] / r_a}{LE} - \Delta \right\} / \gamma - 1 \right) \tag{3}$$

with R_n being the net radiation, G the soil heat flux (W m^{-2}), γ the psychrometric constant (Pa K^{-1}), $e_S(T_a)$ the saturation vapour pressure, e the vapour pressure, and ρ and c_P the air density and specific heat at constant pressure, respectively.

Soil heat flux was assumed as the difference between net radiation and the sum of latent and sensible heat fluxes. Saturation vapour pressure $e_S(T)$ was calculated by the following equation (Campbell and Norman, 1998),

$$e_S(T_a) = 611 \exp \left(\frac{17.502 T_a}{T_a + 240.97} \right) \tag{4}$$

with T_a being air temperature (°C).

The long-term success of afforestation and the associated carbon sequestration potential in semi-arid climates must also be linked to the consequences in surface energy balance (Rotenberg and Yakir, 2010). For a preliminary analysis of the impact of drought in the radiative energy partition between sensible (H) and latent heat (LE) fluxes, we used the Bowen ratio ($\beta = H/LE$). The ratio β is typically 0.4–0.8 for temperate forests and 2–6 for semi-arid areas (Oke, 1992).

Relationships between NEE and PAR were analyzed using half-hour data with higher quality (flags 0 and 1) in the months January, April and August for every year of the period considered. The analysis was restricted only to diurnal data ($R_g > 10\,\mathrm{W\,m^{-2}}$). In 2007, 2008 and 2009, November was additionally analyzed. The fitted expressions using the Marquardt method (Seber and Wild, 1989; SAS software, ver. 9.3.1, procedure NLIN, 2003) were based on the Michaelis–Menten equation,

$$\mathrm{NEE} = \beta - \frac{\gamma \mathrm{PAR}}{\alpha + \mathrm{PAR}} \tag{5}$$

where β is the respiration parameter derived by extrapolating the light response curve to zero irradiance, γ the maximum rate of photosynthetic assimilation and α corresponds to the PAR radiation at which photosynthesis is one half of γ. All variables are expressed in $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$. From these parameters, quantum yield can be obtained as the ratio γ/α.

In order to establish possible useful practical equations relating the main meteorological variables with monthly NEE and GPP for the period preceding tree felling, a modelling approach was done based on the application of general estimating equations (GEEs) methodology. GEEs were developed by Liang and Zeger (1986) in the context of extending generalized linear models to Gaussian and non-Gaussian longitudinal clustered response data (Schabenberger and Pierce, 2002). In GEEs, correlated data are modelled using the same link function and linear predictor as in the general independent case, with the difference that the covariance structure of the correlated measurements must also be modelled.

In this work GEE data analysis was done with the SAS software (ver. 9.3.1) procedure Genmod. Basically GEEs permit a consistent iterative, quasi-likelihood estimation of the vector of regression parameters θ as

$$\hat{\theta}_{r+1} = \hat{\theta}_r + \left(\sum_{i=1}^{N} \frac{\partial \mu_i'}{\partial \theta} \hat{V}_i^{-1} \frac{\partial \mu_i}{\partial \theta} \right)^{-1} \times \frac{\partial \mu_i'}{\partial \theta} \hat{V}_i^{-1} (Y_i - \mu_i) \tag{6}$$

with Y_i and μ_i corresponding, respectively, to the vectors of measurements and means in the ith subject, $\hat{V}_i$ an estimate of V_i, the covariance matrix of Y_i, and N, the total number of measurements. The term corresponding to the inverse of the summation in Eq. (6) is the model-based estimate of V_i, which would be used if $\hat{V}_i$ were the correct variance–covariance matrix. The GEE estimation uses a so-called "sandwich" or empirical estimator of the variance matrix of clustered quantitative variables by the various levels of the classification variables. This estimator includes a working correlation matrix (banded m-dependent, exchangeable or autoregressive), and successive estimates of covariance matrices allow to obtain iterative estimates of regression parameters, till convergence. An adequate choice for the working correlation structure is indicated by a reasonable similarity between matrices of model based and empirical covariance estimators (Hedeker and Gibbons, 2006). The regression coefficients obtained by GEEs are consistent estimators of the population regression parameters (Fitzmaurice et al., 2004).

2.3. Biomass measurements

Measurements of total tree height, crown length and diameter at breast height were made in January 2002, 2003, 2005 and 2006 in five plots of $225\,\mathrm{m}^2$ adjacent to the tower, for allometric estimation of annual carbon biomass. The equations used were those reported by António et al. (2007) for individual trees. Each fraction of biomass was individually estimated as a function of tree diameter, height, crown length and the dominant height of the stand. The total above ground biomass was calculated by the sum of all fractions.

3. Results and discussion

3.1. Meteorological conditions and GEE equations

Table 1 shows, for the whole period, data of NEE and GPP and the concomitant variation of key meteorological variables such as average air temperature (T_a), incoming global radiation (R_g), precipitation (*Prec*), and evapotranspiration (E). These data are aggregated in annual and quarterly periods, aiming to investigate the seasonal and annual variations. Fig. 1 shows a steady seasonal pattern for R_g, phased with T_a in the whole eight year period.

Averaged annual temperatures in 2003, 2004, 2005, 2006 and 2009 exceeded the long term mean of 15.90 °C (Table 1). Annual precipitation was the variable with the most significant variation relatively to the long term average (1961–1990) of 709 mm, with reductions of 47%, 44%, 37%, 29% and 20% comparatively to this average in 2004, 2005, 2007, 2008 and 2009, respectively. The prolonged drought of 2004 and 2005 was the most severe in 140 years (Garcia-Herrera et al., 2007). In 2004, E was 722.55 mm, higher than in 2002 and 2003 and almost twice the precipitation (Table 1) due to soil moisture depletion. In 2005 E decreased to 391.64 mm, of the same order of magnitude of the precipitation.

Monthly patterns of rain events were typically Mediterranean with almost no rainfall on summer months and more precipitation in winter and spring. The years of 2004 and 2005, besides the lower precipitation showed uneven monthly pattern of rain distribution along the year. Indeed, rainfall in the first quarter of 2004 (210.03 mm) corresponded to 55.5% of the precipitation in the whole year (Table 1) and in 2005 about 38% of the scarce rainfall occurred in March and about 40% in the last quarter (Table 1). The bulk evapotranspiration in 2004, 610.86 mm corresponding to 68% of the total, occurred in the period April–December characterized by the lowest rainfall.

Before the felling, the monthly averaged vapour pressure deficit (VPD) followed the trend of drought's seasonal and annual conditions, with averages of 6.18 hPa, 7.56 hPa, 8.67 hPa and 7.31 hPa, in 2002–2003, 2004, 2005 and 2006, respectively. After the felling, the average monthly VPD for 2007–2009 lowered to 5.34 hPa. In the period 2007–2009, soil moisture increased with depth from 3.47% at 10 cm to 11.49% at 1 m, outreaching the wilting point for sandy soils (5%) below 60 cm.

GEE modelling was used for a quantification of the influence of the main meteorological variables in monthly carbon fluxes in the period from January 2002 to October 2006. An extensive analysis of distinct combinations was done regarding: classification (month, year and month nested in year); quantitative variables; and working matrices. The fitted equations, considering identity link function and the attested normal distribution of data, were:

$$\begin{aligned} \mathrm{NEE} &= -42.97 - 0.0903\mathrm{PARm} + 0.0062\mathrm{VPDm} \\ \mathrm{GPP} &= 98.67 + 0.16\mathrm{PARm} + 0.0085\mathrm{VPDm} \end{aligned} \tag{7}$$

where the independent variables are the accumulated monthly data: VPDm (hPa) of VPD, and PARm ($\mathrm{MJ\,m^{-2}}$) of PAR radiation. These equations are plotted in Fig. 2. The classification variable considered in the selected models was the month, and the pro-

Table 2
Models' parameters.

	Confidence limits	Estimate	Standard error	p, z score
Model NEE				
Intercept	−60.7353, −25.212	−42.9736	9.0622	<0.0001, $R^2 = 0.49$
PAR coefficient	−0.1216, −0.059	−0.0903	0.016	<0.0001
VPD coefficient	0.0045, 0.0079	0.0062	0.0009	<0.0001
Model GPP				
Intercept	83.7857, 113.5456	98.6657	7.592	<0.0001, $R^2 = 0.49$
PAR coefficient	0.1354, 0.1843	0.1599	0.0125	<0.0001
VPD coefficient	−0.01, −0,007	0.0085	0.0007	<0.0001

posed working matrices types for these equations were banded 1-dependent (GPP), and autoregressive (NEE).

Table 2 shows some measures of these model equations. Statistics used to select the models were the similarity of empirical and model-based covariance matrices, z scores and p-values for regression parameters. The coefficients R^2, evaluated after the GEE model selection, improved comparatively to the ones of usual regression models.

Eqs. (7) show the influence of meteorological parameters associated with atmospheric humidity and radiation in NEE and GPP in the drought period, and are interesting under a practical point of view. The inclusion of vapour pressure deficit reflects the fact that VPD in forests exerts strong control in photosynthetic uptake (Baldocchi, 1997; McCaughey et al., 2006).

3.2. *Impact of the two events in temporal variation of carbon fluxes*

3.2.1. *Daily patterns*

A simple analysis of the graphs and results of carbon fluxes and meteorological variables at daily, monthly and annual timescales clearly demonstrates the link between variables associated to water stress, e.g., precipitation and water vapour deficit, and NEE and GPP. From Table 1 we can establish a criterion to divide the drought period of 2004 and 2005 in two stages. A first stage corresponds to 2004 with reduction in precipitation and annual carbon fluxes of the same order of magnitude of 2002 and 2003, and a second stage corresponds to 2005 when, under low rainfall, a drastic reduction in carbon uptake occurred.

During the eight year period, the daily uptake of carbon followed distinct patterns reflecting the distinct environmental conditions and disturbances. Inter-annual evolution of daily GPP, NEE, and TER is shown in Fig. 3. In 2002, 2003 and 2004 the percentages of days with carbon uptake were 92%, 90% and 89%, respectively. In 2005, the year when the drought effects in carbon fluxes were greatest, the percentage of days with carbon uptake lowered to 62%. In 2006 the percentage of days with carbon uptake recovered to about 78%, despite the tree felling in October and November. In 2007, 2008 and 2009, carbon uptake occurred in about 50%, 61% and 62% of the days, respectively.

Seasonal patterns of the hourly averaged typical day carbon and latent heat (*LE*) fluxes and meteorological data were analyzed on a quarterly basis in the periods 2002–2003, 2005 and 2008–2009 concerning, respectively, normal productive years, drought and sprouting after the felling (Figs. 4–9. As a rule R_g phased and peaked with NEE and GPP at about noon, whereas TER phased with vapour pressure deficit and air temperature at about 15 h. The phasing of peaks of TER, GPP and NEE with air temperature, VPD, and R_g is indicative of the driving role of these meteorological variables in the distinct carbon fluxes (Falge et al., 2002; Carrara et al., 2004).

In all the periods, an approximate synchrony between typical day curves of GPP and *LE* (not shown) was indicative of the fundamental role of stomatal closure in controlling atmospheric carbon exchanges and evapotranspiration. Typical day curves representative of NEE (Fig. 7), and GPP (Fig. 8) showed asymmetry, with maxima before noon, reflecting the effects of water stress in evapotranspiration and GPP.

In 2004 the typical day patterns (not shown) were similar to 2002 and 2003, revealing approximate phasing between *LE* and GPP curves and asymmetry in the July–September period. In 2005 three of the four NEE and *LE* curves analyzed followed an asymmetric pattern with maximum NEE and GPP occurring in the period January–March (Figs. 7 and 8).

In the period 2008–09 the eucalypt coppice behaved again as a carbon sink. with lower NEE and GPP in comparison to the period corresponding to the end of rotation cycle. The asymmetric patterns of typical day in summer were maintained (Figs. 7 and 8).

3.2.2. *Annual and seasonal patterns*

3.2.2.1. Drought effects. Annual and seasonal patterns of NEE, GPP and TER in the period 2002–2006 are shown in Table 1 and Fig. 11. Before the felling, monthly averaged NEE had averaged maxima of $-102.98\,\mathrm{g\,C\,m^{-2}}$ in mid-spring, and minima in late summer of $-10.53\,\mathrm{g\,C\,m^{-2}}$. This monthly maximum in mid-spring agrees with the discussion by Rotenberg and Yakir (2010) about a tendency of GPP time peaks in European pine forests shifting from July–August to mid-March, with decreasing latitude.

Under environmental conditions appropriate to eucalypt growing, global values of GPP and NEE in Espirra prior to the felling (Table 1) are high, comparatively to data reported in studies for other sites in Europe (e.g. Falge et al., 2002). A prevalence of GPP over total ecosystem respiration at Espirra is evidenced by the higher annual ratios GPP/TER, varying between 1.43 (2005) and 2.13 (2003). These values are higher than those reported by other studies, e.g., 1.35 from a fast growing beech forest of Hesse (France) in an eight year period (Granier et al., 2008), and 1.25 from 18 European forest ecosystems (Janssens et al., 2001).

Annual averaged remotely sensed MODIS LAI (Fig. 10) was 4.72 in 2002, 5.26 in 2003 and 5.33 in 2004, decreasing to 3.58 in 2005

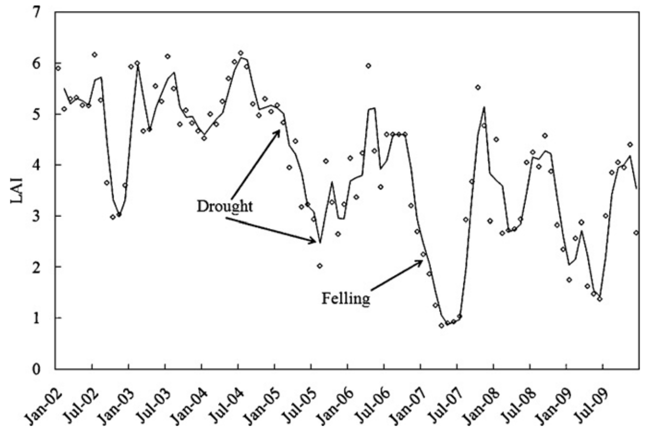


Fig. 10. Monthly averaged MODIS LAI in the whole period: measured values (◊) and moving averages (—).

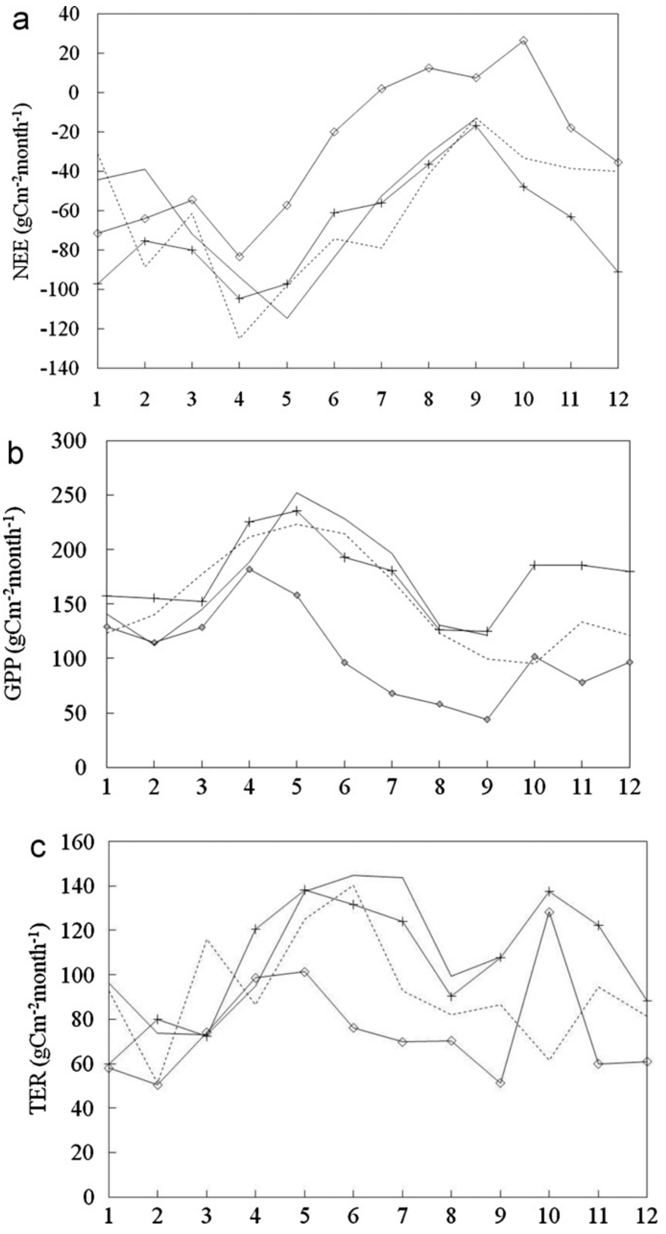


Fig. 11. Monthly averaged atmospheric carbon in the years before the felling: (a) NEE; (b) GPP; (c) TER.

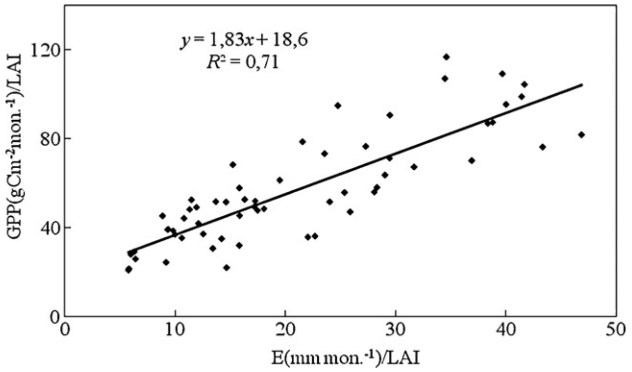


Fig. 12. Monthly variation of ratio GPP/LAI with E/LAI in the period before the felling.

due to leaf yellowing under intense water stress. In 2006, before the felling, annual LAI recovered to 4.37 with a maximum of 5.95 in April.

In the period 2002–2006, monthly and quarterly GPP phased approximately with evapotranspiration (Table 1) as attested by the good linear relationship ($R^2 = 0.71$, Fig. 12) between the monthly ratios GPP/LAI and E/LAI.

Between 2002 and 2006, annual monthly averaged NEE and GPP varied inversely with vapour pressure deficit, with the September fall in carbon uptake coinciding with maxima averaged monthly VPD (Fig. 13). This is due to the fact that forest stomatal conductance tends to be higher at low VPDs, as shown, e.g., by Granier et al. (2000) for a set of 21 broadleaved and coniferous forest stands or by David et al. (1997) for *Eucalyptus globulus* in Portugal.

The effects of drought on NEE and GPP were felt mainly between September 2004 and December 2005 (Fig. 11). This period followed a six month period with a total rainfall of only 39.15 mm and an evaporation of 475.03 mm, when values of GPP, NEE and TER were of similar magnitude as these averaged from the same period in 2002 and 2003 (Fig. 11). In 2005 the totals of NEE ($-356.64\,\mathrm{g\,C\,m^{-2}}$) GPP ($1255.11\,\mathrm{g\,C\,m^{-2}}$) and TER ($898.48\,\mathrm{g\,C\,m^{-2}}$) (Table 1) were substantially lower than in the previous years, and the eucalypt stand behaved as a carbon source from July till November. The prolonged lack of rainfall inducing water stress and lower LAI was determinant for this restriction of carbon atmospheric exchange. Steady patterns of solar radiation and air temperature before the felling were never limiting factors to the development of continuous carbon uptake and photosynthesis along the annual periods.

The influence of drought in restraining carbon fluxes due to water limitations had been shown, e.g., by Migliavacca et al. (2009) in an intensively managed poplar forest in Zerbolò (Italy) and by Reichstein et al. (2002), in two Mediterranean holm oak (*Quercus Ilex*) forests (Puéchabon, France). In the holm oak forests both GPP and respiration are constrained under drought and contingent on soil water contents at different depths. This evidence allows to hypothesize that, under the first drought stage in 2004 and given the low soil water content at surface, roots got access to lower soil depths. Thus, the decrease of GPP was minimized and the drought's most severe consequences were delayed. Indeed, Moroni et al. (2003) indicated that 6 year old *Eucalyptus globulus* trees in Tasmania under drought stressed conditions were encouraged to develop a higher root frequency and length than under irrigated conditions, and were thereby able to penetrate the dry soil. The worst effects of drought were shown in 2005 when, despite the possibility of the trees to develop a root system able to tap water at deeper soil depth, water replenishment by the scarce rainfall was not enough to sustain the same levels of GPP as before.

NEE and γ in January–March 2005 (Figs. 10 and 17) were $-190.29\,\mathrm{g\,C\,m^{-2}}$ (Table 1), and $25.37\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$, high when compared to equivalent periods in other years (e.g., 2002, or 2006, Table 1). This fact was mainly determined by the lower values of mean air temperature in January (8.94 °C) and February (8.71 °C) 2005, which restricted TER in the first quarter to $182.15\,\mathrm{g\,C\,m^{-2}}$ (Table 1). This TER value, simultaneous with a drought-induced decrease in GPP to $372.44\,\mathrm{g\,C\,m^{-2}}$, was the second lowest in the same periods of the years included in this study. In conjunction with air cooling, a precipitation of only 7.65 mm in January and February 2005 probably also contributed to a strong restraining of microbial soil respiration, enhancing thereby net carbon uptake.

The last month when the ecosystem behaved as carbon source (Fig. 11) was October 2005, when an increase of precipitation to 154.07 mm, corresponding to 39% of the annual total, replenished available water in the ecosystem resulting in peaks both in TER ($128.34\,\mathrm{g\,C\,m^{-2}}$), due mainly to soil respiration, and GPP ($101.68\,\mathrm{g\,C\,m^{-2}}$).

The decrease in carbon uptake in 2005 was due mostly to a decrease in GPP. Indeed, on an average monthly basis, GPP in 2005

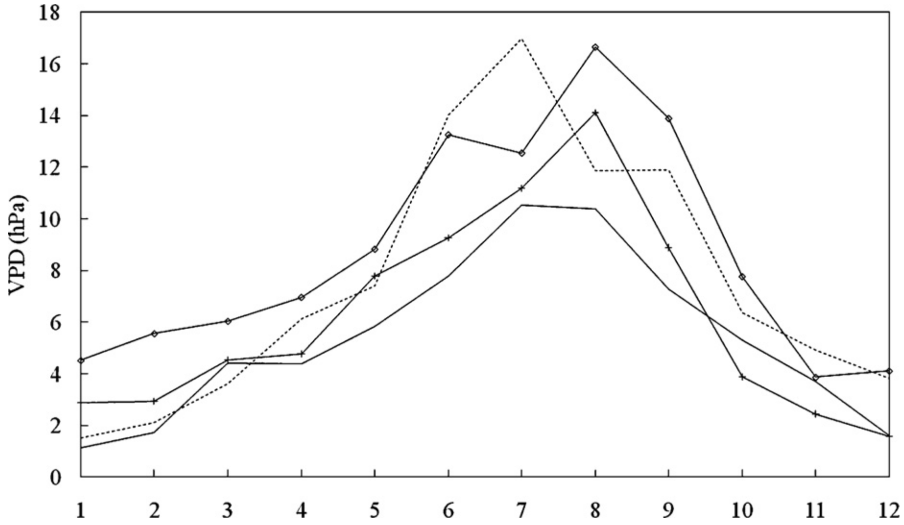


Fig. 13. Monthly averaged VPD in the whole period excepting 2006 (+, 2002–2003; - - -, 2004, ◊, 2005; —, 2007–2009).

decreased by about 35% relatively to the remaining years before the felling. The corresponding decrease in TER was 18%. The averaged monthly ratio between GPP and TER decreased from 2.13 in 2003 to 1.69 in 2004 and 1.43 in 2005, increasing to 1.58 in 2006. In the Mediterranean holm oak forest under drought conditions (Reichstein et al., 2002) the decline in this ratio is a symptom indicative of low soil water availability. Soil dryness induces a hormonal signal sent from the roots, causing stomatal limitation of gas exchanges (Baldocchi, 1997). The preponderance of GPP decrease agrees with the studies of Valentini et al. (2000) and Falge et al. (2002) concluding that the importance of ecosystem respiration in carbon exchange in European ecosystems increases with latitude.

In 2006 with the increase of precipitation, the eucalypt stand recovered its carbon sink capacity (Fig. 11) with a NEE of −544.38 g C m^{-2} in the months till the felling, equivalent to the carbon uptake in the same period of a normal year (e.g., 2002). The fast recovery of GPP and NEE after the drought, reflects the canopy plasticity and the reversibility of the mechanisms responsible for the drop of GPP and NEE in 2005.

3.2.2.2. Felling effects. The eucalypt stand recovered its sink capacity after June 2007, to totals of −200.73 g C m^{-2} and −209.01 g C m^{-2} in 2008 and 2009 (Fig. 14). In these years, carbon uptake lasted 233 days, from mid February till mid October, following thereby a pattern almost opposite to the trees in the term of their productive cycle. Monthly γ and quantum yield variation (Fig. 17) agreed with the reduction of carbon uptake and with the change of carbon uptake's seasonal pattern.

As happened with drought, the reduction in carbon uptake in 2008 and 2009 was due mostly to a decrease in GPP. Indeed, the monthly averages of GPP and TER decreased, respectively, 38% and 15% in 2008–2009 as compared to 2002–2003.

An estimated 13.6 ton biomass ha^{-1} of litter (leaves, branches and twigs) left in the soil, corresponding to about 10% of the total biomass, remained after the felling in 2006. The heterotrophic decomposition of this biomass contributed to the high values, above 920 g C m^{-2}, of annual TER in 2007–2009 (Table 1).

The main explanation to the change of NEE seasonal pattern of young trees in 2008 and 2009, under similar weather conditions,

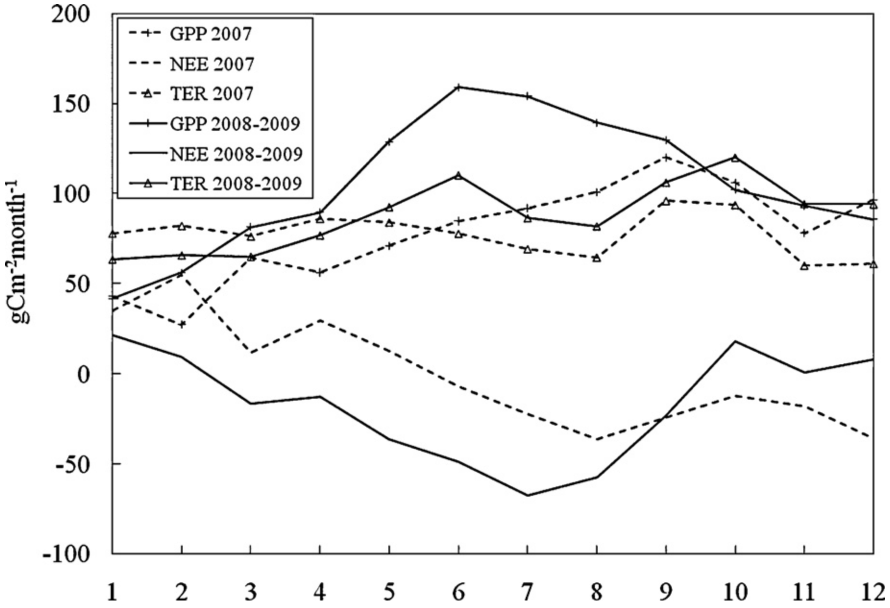


Fig. 14. Monthly averaged carbon fluxes in the period after the felling.

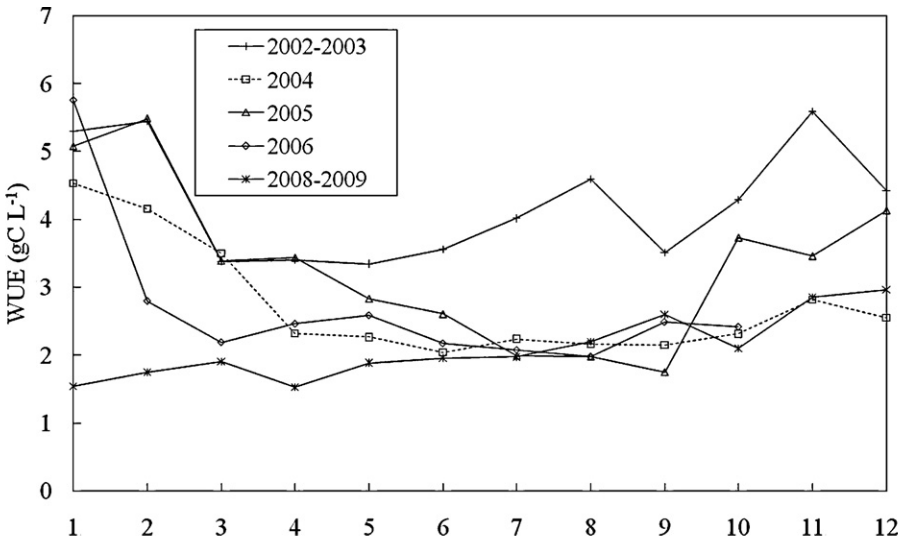


Fig. 15. Monthly variation of WUE in the whole period.

should be related to an improvement of summer water stress conditions, attested by a smaller asymmetry of NEE (Fig. 7) and *LE* typical day curves. This improvement was mostly due to the fact that the young coppice inherited from the felled trees a deep root system, which remained in the soil. The resulting imbalance between the root system and aerial plant in the coppice reduced the shoot/root biomass ratio of about 4.29 in mature eucalypt trees (Madeira et al., 2002) by a factor of about 3.20. The deep roots were therefore possibly able to extract enough water in summer below the 60 cm level, where soil moisture was higher than the wilting point of 5%, and water stress was minimized sustaining stomatal carbon uptake in a new canopy with smaller aerial plant size and lower LAI. Summer water stress after felling was also minimized both by a more scattered distribution of annual precipitation along the years and by reduced atmospheric VPD (Fig. 13).

Monthly averaged remotely sensed MODIS LAI also decreased to 2.41, 3.46 and 2.80 in 2007, 2008 and 2009, respectively (Fig. 10). During the three years after the felling, monthly LAI, GPP and NEE decreased in winter, due to the thinning in October to November 2008 and to the effects of frost in young leafs in winter in 2007, 2008 and 2009. Height growing of young trees, reaching about 7 m in October 2009, agreed with data from growing tables available for the eucalypt site (Goes, 1977).

3.2.3. *WUE, energy partition and evapotranspiration regime*

On a monthly basis, annual averaged water use efficiency, WUE, defined as the ratio of GPP to *E*, decreased from 2002 (4.84 g/L) and 2003 (3.36 g/L) to 2004 (2.75 g/L) and 2005 (3.32 g/L) (Fig. 15) with the onset of drought and increase in soil evaporation and VPD.

In 2004 with the beginning of the increase of evapotranspiration a steep decrease in monthly WUE occurred in April (Fig. 15) to 2.32 g/L, followed by a stationary pattern in the rest of the year. Monthly WUE showed higher seasonal variation in 2005 with a two-month peak in January and February 2005 caused by a drastic decrease in *E* (5.07 g/L and 5.48 g/L), heightening the annual average to 3.32 g/L. A decrease in WUE followed with minima below 2 in July–September, due to a steeper decrease of GPP. Thus, drought under its first stage in 2004 depressed monthly WUE due mostly to an increase in evapotranspiration. In 2005, under the second stage, the decrease in WUE was caused by the high decrease in GPP.

To our knowledge, most studies with analysis of WUE patterns in forest ecosystems concern short drought summer periods. We think that, under a two year drought, the non-steady monthly WUE evolution reflects a more complex interaction between the fundamental underlying stomatal control, evident from phased curves of daily and seasonal GPP and *E*, and other non-stomatal factors (Baldocchi, 1997; Reichstein et al., 2002), e.g., decrease in mesophyll conductance, stomatal patchiness, and dynamics of soil moisture. In 2002 and 2003 the lesser monthly averaged VPD and decreased water stress were factors determinant to higher WUE, allowing also for a steadier monthly pattern. A steady pattern of monthly WUE, prevailed after January 2006 as well.

After the felling, annual averaged monthly WUE were 1.62 g/L, 1.86 g/L and 2.35 g/L, in 2007, 2008 and 2009 respectively, showing an increasing tendency, still lower than this in mature trees, motivated mainly by the lower GPP.

In the context of a prolonged drought, annual average monthly Bowen ratio was 0.55 in 2004 peaking to 1.70 in 2005, a value typical of transition from temperate to semi-arid regions (Oke, 1992). Bowen ratio lowered in 2004, under the drought's first stage, when *LE* increased to almost twice the precipitation, due to the depletion of available soil water. The higher Bowen ratio in the drought's second stage reflected a shift in radiant energy dissipation from evapotranspiration to convective heating and certainly contributed to an increase in leaf temperatures, promoting foliar photorespiration and reduction of carbon gain (Migliavacca et al., 2009; Reichstein et al., 2002).

Monthly evolution of decoupling coefficient, Ω, obtained by inverting the Penman–Monteith equation is shown in Fig. 16. Summer decreases in all the years before felling reflected fluctuating atmospheric vapour pressure deficit and water stress conditions. Annual averaged values of Ω in 2004 and 2005 were 0.26 and 0.11, respectively. This increase in coupling to weather conditions also shows what happened in the drought's two stages. Under the first stage in 2004 in a context of low rainfall, the high annual evaporation (722.55 mm, Table 1) was more dependent on the ecosystem's available radiant energy, and in the second stage in 2005 stomatal control reinforced its role in restraining total evaporation (391.64 mm), contributing to the increase in Bowen ratio.

In the period from 2007 to 2009, the mean Ω value was 0.30 (Fig. 16), with a monthly flatter pattern along these years, with no decrease in summer. Thus, as expected, the sparser canopy of younger plants showed a lesser coupling to weather conditions than the denser canopy of trees corresponding to the end of their productive cycle.

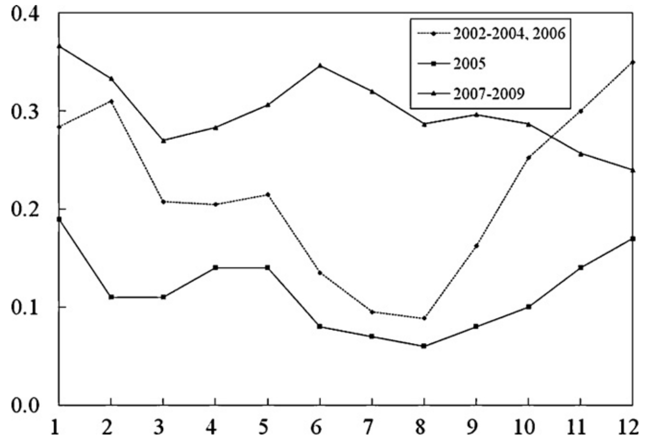


Fig. 16. Monthly variation of Ω, decoupling coefficient, in the whole period.

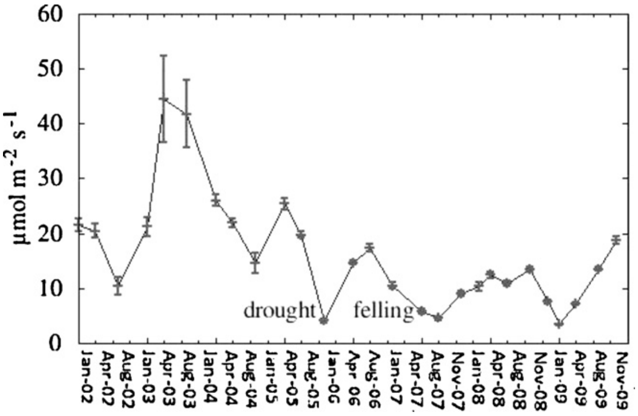


Fig. 17. Variation of γ coefficient in the whole period. (Vertical segments: standard error.)

3.2.4. Michaelis–Menten equations

Michaelis–Menten parameterization showed the tendencies of NEE discussed above. The determination coefficient (R^2) of the fit ranged from 0.11 to 0.86, the lower value in August 2005, reflecting the full impact of drought's second stage and decreased LAI in the diminishing of the contribution of PAR to NEE. In the remaining years before the felling R^2 was lower in August, due to atmospheric water stress constraining the influence of solar radiation in carbon uptake.

Before the felling, fitted γ (maximum rate of photosynthetic assimilation) and quantum yield averaged 20.94 μmol m^{-2} s^{-1} (Fig. 17) and 0.041 respectively and were always lower in August than in April. In this period, January values of fitted γ were higher than August ones, except in 2003, as a consequence of decreased summer carbon uptake. The impact of the 2005 drought and of the felling in 2006 was also reflected by the diminishing of the fitted γ coefficient.

After the felling, averaged fitted γ and quantum yield decreased to 9.74 μmol m^{-2} s^{-1} and 0.035, respectively. In 2008 and 2009, quantum yield and γ were more relevant in August than before the felling, due to the opposite seasonal pattern of NEE and GPP discussed above.

4. Conclusions

The main objective of this study was the analysis of the evolution, in the period 2002–2009, of carbon exchanges in the full year growth eucalypt Espirra site and its relationships to two main events occurred: a long drought period between 2004 and 2005, and a tree felling in October and November 2006.

The impact in NEE and GPP of the strong reduction of annual precipitation in 2004 and 2005 to about 47% and 44% of the long term mean was felt mostly in 2005. Indeed annual NEE increased from −856.56 g C m^{-2} in 2002, −791.33 g C m^{-2} in 2003 and −724.24 g C m^{-2} in 2004, respectively, to −356.64 g C m^{-2} in 2005. This impact, beginning in April 2004, was twofold. In a first stage, in 2004, evapotranspiration almost doubled precipitation due to soil depletion, and NEE (−791 g C m^{-2}) and GPP (1834 g C m^{-2}) were not affected by the reduction of 47% of annual precipitation relatively to the long-term mean. The effects of drought were felt mainly in a second stage in 2005 when: evapotranspiration fell to 391.64 mm, of the same order of magnitude of precipitation; decoupling coefficient decreased to 0.11; Bowen ratio increased to 1.70; and NEE and GPP were reduced to −357 g C m^{-2} and 1255 g C m^{-2}, respectively. The seasonal pattern of carbon uptake in the period preceding the felling, characterized by a peak in late spring and a decrease in summer due to water stress, was not changed in 2005. Average typical day curves of *LE* and GPP phased, and their asymmetry increased in drought periods due to water stress and stomata control of tree transpiration. The reported decrease of NEE as a consequence of the two events was due mostly to a decrease to GPP. Average monthly WUE under the two events also diminished, except for January and February 2005. A GEE modelling approach to the carbon fluxes before the felling allowed for a quantification of the influence of VPD, PAR, radiation and precipitation on NEE and GPP on a monthly basis.

As expected, the felling induced a drastic reduction of sink capacity, with the young eucalypt coppice behaving as a carbon source in the first seven months of the new rotation. The seasonal pattern of GPP in 2008 and 2009, with a higher level in summer and a decrease in winter, was distinct from the one before the felling. In summer, this was due mainly to an enhanced capacity of the deep root system of young plants, inherited from the canopy, to extract water from deeper soil horizons, thereby minimizing summer water stress. The decrease of GPP in winter was mainly related to the diminishing of LAI motivated by an enhanced sensitivity of young leaves and shoots to frost and harsher weather conditions. The Michaelis–Menten parameters (maximum rate of photosynthetic assimilation and quantum yield) followed the seasonal tendencies of NEE before and after the felling.

All the results demonstrated the ability of the eucalypt forest as an annual carbon sink, the interplay between atmospheric carbon and water fluxes, and the clear restricting role of this drought in the carbon sinking at daily, seasonal and annual timescales. Long-term Mediterranean forest climate projections should thereby address the impact of prolonged droughts in carbon sequestration, under distinct scenarios.

Acknowledgements

This research was supported by: Integrated Project CarboEurope (IP Directorate-General Research), 6th Framework Programme, Priority 1.1.6.3, Global Change and Ecosystem, Contract No. GOCE-CT-2003-505572; the Project PPCDT/CLI/60006/2004, "Interaction between water and carbon cycles in a eucalyptus stand"; and Project PTDC/AGR-CFL/69733/2006, "Modelling Net Primary Production and Carbon balance of Portuguese Forest Ecosystems at different scales", Fundação para a Ciência e a Tecnologia (Portugal).

The authors thank the field facilities made available by Portucel (Herdade da Espirra: "Grupo Portucel Soporcel", Complexo Industrial de Setúbal, PO Box 55, 2901-861 Setúbal, Portugal) and their respective institutions, namely: 1st author (A. Rodrigues), Instituto Nacional de Recursos Biológicos (National Institute for Biological

Resources); and corresponding author (M. Casquilho), Centro de Processos Químicos (Centre for Chemical Processes, Technical University of Lisbon).

References

António, N., Tomé, M., Soares, P., Tomé, J.A., Fontes, L., 2007. Effect of stand and site variables on the estimation of aboveground tree biomass of *Eucalyptus globulus*. Canadian Journal of Forest Research 37, 895–906.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A.S., Martin, P.H., Berbigier, P., Bernhofer, Ch., Clement, R., Elbers, J.A., Granier, A., Grünwald, T., Morgenstern, K., Pillegaard, K., Rebmann, C., Snijders, W., Valentini, R., Vesala, T., 2000. Estimates of the annual net carbon and water exchange of forests: EUROFLUX methodology. Advances in Ecological Research 30, 113–175.

Baldocchi, D., 1997. Measuring and modelling carbon dioxide and water vapour exchange over a temperate broad-leaved forest during the summer drought. Plant, Cell and Environment 20, 1108–1122.

Baldocchi, D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Global Change Biology 9, 479–492.

Burba, G., McDermit, D.K., Grelle, A., Anderson, D.J., Xu, L., 2008. Addressing the influence of instrument surface heat exchange on the measurements of CO_2 flux from open-path gas analyzers. Global Change Biology 14 (8), 1854–1876.

Campbell, G.S., Norman, J.M., 1998. An Introduction to Environmental Biophysics. Springer Verlag, 286 pp.

Canadell, J.G., Raupach, M.R., 2008. Managing forests for climate change mitigation. Science 320, 1456–1457.

Carrara, A., Janssens, I., Yuste, J., Ceulemans, R., 2004. Seasonal changes in photosynthesis, respiration and NEE of a mixed temperate forest. Agricultural and Forest Meteorology 126, 15–31.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogee, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D., Friedlingstein, P., Grunwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., Valentini, R., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437, 529–533.

David, T.S., Ferreira, M.I., David, J.S., Pereira, J.S., 1997. Transpiration from a mature *Eucalyptus globulus* plantation in Portugal during a Spring–Summer period of progressively higher water deficit. Oecologia 110, 153–158.

Falge, E., Baldocchi, D.D., Tenhunen, J., Aubinet, M., Bakwin, P., Berbigier, P., Bernhofer, C., Burba, G., Clement, R., Davis, K.J., Elbers, M., Goldstein, A.H., Grelle, A., Granier, A., Gudmundsson, J., Hollinger, D., Kowalski, A.S., Katul, G., Law, B.E., Malhi, Y., Meyers, T., Monson, R.K., Munger, J.W., Oechel, W., Paw, U., Pilegaard, K.T., Rannik, K., Rebmann, U., Suyker, C., Thorgeirsson, A., Valentini, H., Wilson, R., Wofsy, K.S., 2002. Seasonality of ecosystem respiration and gross primary production as derived from FLUXNET measurements. Agricultural and Forest Meteorology 113, 53–74.

FAO, 2010. Global Forest Resources Assessment 2010. Main report. FAO Forestry paper 163. Rome. ISBN 978-92-5-106654-6.

Farquhar, G.D., Sharkey, T.D., 1982. Stomatal conductance and photosynthesis. Annual Review Plant Physiology 33, 317–345.

Fitzmaurice, G.M., Laird, N.M., Ware, J.H., 2004. Applied Longitudinal Analysis. John Wiley, 506 pp.

Garcia-Herrera, R., Paredes, D., Trigo, R.M., Trigo, I.F., Hernandez, E., Barriopedro, D., Mendes, M.A., 2007. The outstanding 2004/05 drought in the Iberian Peninsula: associated atmospheric circulation. Journal of Hydrometeorology 8, 483–498.

Gash, J.H.C., Culf, A.D., 1996. Applying linear detrend to eddy correlation data in real time. Boundary Layer Meterology 79, 301–306.

Göckede, M., Mauder, M., Foken, T., 2005. Report on results of the site Espirra (PTEsp). CarboEurope-IP Activity 1.2, Task 1.2.1. Footprint and quality assessment of main fluxsites.

Göckede, M., Foken, T., Aubinet, M., Aurela, M., Banza, J., Bernhofer, C., Bonnefond, J.M., Brunet, Y., Carrara, A., Clement, R., Dellwik, E., Elbers, J., Eugster, W., Fuhrer, J., Granier, A., Grünwald, T., Heinesch, B., Janssens, I.A., Knohl, A., Koeble, R., Laurila, T., Longdoz, B., Manca, G., Marek, M., Markkanen, T., Mateus, J., Matteucci, G., Mauder, M., Migliavacca, M., Minerbi, S., Moncrieff, J., Montagnani, L., Moors, E., Ourcival, J.-M., Papale, D., Pereira, J., Pilegaard, K., Pita, G., Rambal, S., Rebmann, C., Rodrigues, A., Rotenberg, E., Sanz, M.J., Sedlak, P., Seufert, G., Siebicke, L., Soussana, J.F., Valentini, R., Vesala, T., Verbeeck, H., Yakir, D., 2008. Quality control of CarboEurope flux data. Part 1. Coupling footprint analyses with flux data quality assessment to evaluate sites in forest ecosystems. Biogeosciences 5, 433–450.

Goes, E., 1977. Os Eucaliptos: (Ecologia, Cultura, Produções e Rentabilidade); Portucel, Lisbon, 420 pp.

Granier, A., Loustau, D., Bréda, N., 2000. A generic model of forest canopy conductance dependent on climate, soil water availability and leaf area index. Annals of Forest Science 57, 755–765.

Granier, A., Reichstein, M., Breda, N., Janssens, I.A., Falge, E., Ciais, P., Grunwald, T., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Facini, O., Grassi, G., Heinesch, B., Ilvesniemi, H., Keronen, P., Knohl, A., Kostner, B., Lagergren, F., Lindroth, A., Longdoz, B., Loustau, D., Mateus, J., Montagnani, L., Nys, C., Moors, E., Papale, D., Peiffer, M., Pilegaard, K., Pita, G., Pumpanen, J., Rambal, S., Rebmann, C., Rodrigues, A., Seufert, G., Tenhunen, J., Vesala, T., Wang, Q., 2007. Evidence for soil water control on carbon and water dynamics in European forests during the extremely dry year: 2003. Agricultural and Forest Meteorology 143, 123–145.

Granier, A., Bréda, N., Longdoz, B., Gross, P., Ngao, J., 2008. Ten years of fluxes and stand growth in a young beech forest at Hesse, North-eastern France. Annals of Forest Science 64 (704), 1–13.

Greco, S., Baldocchi, D.D., 1996. Seasonal variations of CO_2 and water vapour exchange rates over a temperate deciduous forest. Global Change Biology 2, 183–197.

Hedeker, D., Gibbons, R., 2006. Longitudinal Data Analysis. John Wiley, 337 pp.

Janssens, I.A., Lankreijer, H., Matteucci, G., Kowalski, A.S., Buchmann, N., Epron, D., Pilegaard, K., Kutsch, W., Longdoz, B., Grünwald, T., Montagnani, L., Dore, S., Rebmann, C., Moors, E.J., Grelle, A., Rannik, U¨., Morgenstern, K., Clement, R., Gudmundsson, J., Minerbi, S., Berbigier, P., Ibrom, A., Moncrieff, J., Aubinet, M., Bernhofer, C., Jensen, N.O., Vesala, T., Granier, A., Schulze, E.D., Lindroth, A., Dolman, A.J., Jarvis, P.G., Ceulemans, R., Valentini, R., 2001. Productivity and disturbance overshadow temperature in determining soil and ecosystem respiration across European forests. Global Change Biology 7, 269–278.

Jiang, H., Apps, M., Peng, C., Zhang, Y., Liu, J., 2002. Modelling the influence of harvesting on Chinese boreal forest carbon dynamics. Forest Ecology and Management 169, 65–82.

Lebaube, S., Le Goff, N., Ottorini, J.-M., Granier, A., 2000. Carbon balance and tree growth in a Fagus sylvatica stand. Annals of Forest Science 57, 49–61.

Liang, K.-Y., Zeger, S.L., 1986. Longitudinal data analysis using generalized linear models. Biometrika 73, 13–22.

Madeira, M.V., Fabião, A., Pereira, J.S., Araújo, M.C., Ribeiro, C., 2002. Changes in carbon stocks in *Eucalyptus globulus* Labill. plantations induced by different water and nutrient availability. Forest Ecology and Management 171, 75–85.

Markewitz, D., 2006. Fossil fuel carbon emissions from silviculture: impacts on net carbon sequestration in forests. Forest Ecology and Management 236, 153–161.

Mateus, J., Pita, G., Rodrigues, A., 2006. Seasonality and inter-annual forest atmosphere carbon and water exchanges in a Portuguese eucalyptus plantation (Mediterranean climate). In: Presentation to the 27th Conference on Agricultural and Forest Meteorology , San Diego, USA.

Mauder, M., Foken, T., 2004. CarboEurope-IP Task 1.2.2. Quality control of eddy covariance measurements (C: 0,1,2).

McCaughey, J., Pejam, M., Arain, M., Cameron, D., 2006. Carbon dioxide and energy fluxes from a boreal mixed wood forest ecosystem in Ontario, Canada. Agricultural and Forest Meteorology 140, 79–96.

Migliavacca, M., Meroni, M., Manca, G., Matteucci, G., Montagnani, L., Grassi, G., Zenone, T., Teobaldelli, M., Goded, I., Colombo, R., Seufert, G., 2009. Seasonal and interannual patterns of carbon and water fluxes of a poplar plantation under peculiar eco-climatic conditions. Agricultural and Forest Meteorology 149, 1460–1476.

Miranda, P., Coelho, F.E.S., Tomé, A.R., Valente, M.A., 2002. In: Santos, F.D., Forbes, K., Moita, R. (Eds.), 20th Century Portuguese Climate and Climate Scenarios. Climate Change in Portugal. Scenarios, Impacts, and Adaptation Measures. Gradiva, Lisbon, Portugal, pp. 25–83.

Monteith, J.L., Unsworth, M.H., 1990. Principles of Environmental Physics. Edward Arnold, London, 291 pp.

Moroni, M.T., Worledge, D., Beadle, C.L., 2003. Root distribution of *Eucalyptus nitens* and *E. globulus* in irrigated and droughted soil. Forest Ecology and Management 177, 399–407.

Oke, T.R., 1992. Boundary Layer Climates, 2nd edition. Routledge, 435 pp.

Papale, D., Reichstein, M., Aubinet, M., Canfora, E., Bernhofer, C., Kutsch, W., Longdoz, B., Rambal, S., Valentini, R., Vesala, T., Yakir, D., 2006. Towards a standardized processing of net ecosystem exchange measured with eddy covariance technique: algorithms and uncertainty estimation. Biogeosciences 3, 571–583.

Paquette, A., Messier, C., 2010. The role of plantations in managing the world's forests in the Anthropocene. Frontiers in Ecology and the Environment 8 (1), 27–34.

Pereira, J.S., Tenhunen, J.D., Lange, O.L., Beyschlag, W., Meyer, A., David, M.M., 1986. Seasonal and diurnal patterns in leaf gas exchange of *Eucalyptus globulus* Labill. trees growing in Portugal. Canadian Journal of Forest Research 16, 177–184.

Pereira, J.S., Mateus, J.A., Aires, L.M., Pita, G., Pio, C., David, J.S., Andrade, V., Banza, J., David, T.S., Paço, T.A., Rodrigues, A., 2007. Net ecosystem carbon exchange in three contrasting Mediterranean ecosystems—the effect of drought. Biogeosciences 4, 791–802.

Reichstein, M., Tenhunen, J.D., Roupsard, O., Ourcival, J.M., Rambal, S., Miglietta, F., Peressotti, A., Pecchiari, M., Tirone, G., Valentini, R., 2002. Severe drought effects on ecosystem CO_2 and H_2O fluxes at three Mediterranean evergreen sites: revision of current hypotheses? Global Change Biology 8 (10), 999–1017.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grunwald, T., Havrankova, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentini, R., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Global Change Biology 11 (9), 1424–1439.

Rodrigues, A., Pita, A., Mateus, J., 2005. Turbulent fluxes of carbon dioxide and water vapour over a eucalyptus forest in Portugal. Silva Lusitana 13, 169–180.

Rotenberg, E., Yakir, D., 2010. Contribution of semi-arid forests to the climate system. Science 327, 451–454.

SAS, 2003. Ver. 9.1.3. SAS Institute Inc., Cary, NC (USA).

Schabenberger, O., Pierce, F.J., 2002. Contemporary Statistical Models for the Plant and Soil Sciences. CEC, 738 pp.

Schmid, H.P., Grimmond, C.S.B., Cropley, F., Offerle, B., Su, H.-B., 2000. Measurements of CO_2 and energy fluxes over a mixed hardwood forest in the mid-western United States. Agricultural and Forest Meteorology 103, 357–374.

Schotanus, E.K., Nieuwstadt, F.T.M., de Bruin, H.A.R., 1983. Temperature measurement with a sonic anemometer and its application to heat and moisture flux. Boundary-Layer Meteorology 26, 81–93.

Seber, G.A.F., Wild, C.J., 1989. Non Linear Regression. John Wiley, 769 pp.

Tenhunen, J.D., Lange, O.L., Harley, P.C., Beyschlag, W., Meyer, A., David, M.M., 1985. Limitations due to water stress of leaf net photosynthesis of Quercus Coccifers in the Portuguese evergreen scrub. Oecologia 67, 23–30.

Valentini, R., Matteucci, G., Dolman, A.J., Schulze, E.D., Rebmann, C., Moors, E.J., Granier, A., Gross, P., Jensen, N.O., Pilegaard, K., Lindroth, A., Grelle, A., Bernhofer, C., Grunwald, T., Aubinet, M., Ceulemans, R., Kowalski, A.S., Vesala, T., Rannik, U., Berbigier, P., Loustau, D., Gudmundsson, J., Thorgeirsson, H., Montagnani, L., Minerbi, S., Jarvis, P.G., 2000. Respiration as the main determinant of carbon balance in European forests. Nature 404, 861–865.

Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Quarterly Journal of the Royal Meteorological Society 106, 85–100.

Xiao, C.W., Yuste, J., Janssens, I., Roskams, N.L., Carrara, A., Sanchez, B., Ceulemans, R., 2003. Above- and belowground biomass and net primary production in a 73-year old Scots pine forest. Tree Physiology 23, 505–516.