Abstract

In Portugal eucalypt (*Eucalyptus globulus Labill.*) stands aimed mainly for pulp production, occupy an area of 739515ha, corresponding to 23% of total forest area. The main objective of this work was to report the recovery of seasonal pattern of GPP in a eucalypt site in Pegões (Southern Portugal) after a felling processed in October - November 2006. The site was part of a 300 ha eucalypt stand, located in Herdade da Espirra, with a density of about 1100 trees/ha. The stand was intensively managed as a coppice under a twelve year productive cycle and characterized by a 12-month growing period. Carbon fluxes data in this site have been measured by eddy covariance in the period 2002-2010. A prolonged two stage drought in 2004 and 2005, when rainfall was reduced to values of 50% above the long-term mean term, and a clearcutting in October–November 2006, followed by the start of a new production cycle, changed the carbon sink ability of eucalypt stand. In the period prior to cutting GPP (2204,0 g m^{-2}) was maximum in 2002 decreasing to a minimum of 1255,1 g m^{-2} in 2005 at the peak of the drought effect. Eight months after the felling young shoots emerging from stumps grew very fast and new trees reached an average 8m height in 2010. In June 2007 the eucalypt stand recovered its carbon sink capacity with an annual GPP of 1621.6 g cm^{-2} in 2010. Seasonal patterns of GPP in 2008 and 2009 with maximum carbon uptake occurring from mid-February to mid-October were almost opposite to that of the period before the felling when leaf stomatal control prevented major water losses under summer water stress The fast recovery of the young eucalypt stand was due to the maintenance of a viable and mature root system. In 2010 GPP monthly variation showed a pattern analogous to the period prior to drought.

1 Introduction

The importance of global warming driven by greenhouse gases, especially carbon dioxide, caused by anthropogenic activities (IPCC, 2007) such as combustion of fossil fuels and deforestation is unquestionable. Climate change is of utmost importance in Mediterranean countries like Portugal with dry and hot summer periods and discrete intense rainy episodes occurring mainly in autumn and winter. In Portugal air temperature increased since 1975 at a rate of 0,5ºC per decade(Tomé and Miranda, 2004), and eleven of the warmest years between 1860 and 2006 occurred during the 12 years prior to 2006 (Viterbo, 2011).

In Mediterranean climates, with mean annual rainfall of about 700-800 mm, another feature inherent in the context of climate change is the occurrence anomalies concerning frequency and severity of drought periods. The prolonged drought occurred in 2004 and 2005 in Iberian Peninsula was thereby the most severe of the last 140 years (Garcia-Herrera et al., 2007). Scenarios for climactic evolution in Portugal based on global scale models point out to air temperature increases of 3ºC to 7ºC and precipitation losses of 20% to 40% till the end of the XXIth century.

In this entire context the problem of afforestation with exotic fast growing tree species assumes particular interest. In Portugal, eucalypt (*Eucalyptus globulus Labill.*) is a exotic forest specie introduced in the mean 1800s. Nowadays eucalypt stands are submitted to intensive management aimed primarily for pulp production, with high wood productivity of about $16m^3\ ha^{-1}\ year^{-1}$, occupying an area of about 739515 ha, corresponding to about 23% of total forest area (National Forest Inventory 2005-2006).

Over the past 20 years the scientific knowledge on eddy covariance methodology (Aubinet et al., 2000, Reichstein et al., 2005, Papale et al. 2006) and on the factors affecting NEE, GPP and TER in forests improved substantially. This was due to research projects such as Carboeuroflux (2000–2003), Carboeurope (2004–2008) or scientific networks such as Fluxnet. Among these are factors linked to weather, latitude, (Valentini et al. 2000) or season of the year (Falge et al.2002), tree biology, duration of the growing season or temperature and soil moisture (Schmidt et al. 2000). In Mediterranean climates, carbon sequestration is decisively influenced by water stress of the ecosystem (Reichstein et al.,2002) and atmospheric flows governed by the dynamics of the functioning of stomata, under conditions of severe summer water stresses (Granier et al., 2007; Pereira et al.,2007; Rodrigues et al., 2011). Relationships between NEE, GPP and water vapor deficit and photosynthetic active radiation may be obtained e.g. by general estimating equations modeling (Rodrigues et al., 2011).

Concerning eucalypt species, available evidence from hydrological studies show that besides fast-growing carbon fixation, such species tend to have very effective stomatal response mechanism to soil moisture deficits and vapor pressure deficit (*VPD*) that allow trees to survive droughts (Newson and Calder, 1989, Pereira et al. 2007). With *Eucalyptus globulus* Labill., available information points to stomatal responses above *VPD* thresholds of 1,2kPa (Newson and Calder, 1989; Rodrigues et al. 2011).

Another general principle applied to some eucalypt species is that when the atmospheric evaporative demand is high and trees still have water reserves in the soil, high rates of evapotranspiration can occur (Newson and Calder, 1989). Annual rates of transpiration in *Eucalyptus globulus* 2700 mm, an order of four times the annual rainfall of 680mm were listed on the site of Hotham Valley in Western Australia (Greenwood et al., 1985). Hydrological studies in eucalypt stands in Portugal and Spain (David et al., 1994, Fernández et al., 2006) also show that mature and deep root system allows to a fast regeneration of the eucalypt stand after a clear felling with substantial increases in evapotranspiration in a short period (3-4 years) after felling. This fast regeneration is linked to significant growth in tree height and LAI (Soares *et al*. 2007). The drastic reduction in aerial biomass after felling simultaneous with an active root system typical of trees mature in their term of production cycle allow to young shoots to withstand severe summer water stress. One of the main effects of water deficits is precisely to limit leaf growing and canopy expansion (Osório et al., 1998).

During the period 2002–2010, two main events happened in the eucalypt site with drastic consequences on the ability of carbon assimilation by the ecosystem, namely a prolonged drought in 2004–2005 and a tree felling in October–November 2006.

The effects of two phase drought in carbon fixation were analyzed in another paper (Rodrigues et al., 2011). In the period 2008-2009 seasonal patterns of GPP, with carbon uptake active from mid-February to mid-October and nearly stopping in winter due to frost, were almost opposite to the period before the felling when leaf stomatal closure preventing transpiration cancelled carbon uptake in Summer.In 2010 GPP monthly variation in the young matured stand recovered the pattern prior to the clearcutting.

In this study, considering the whole 2002-2010 period, we focused mainly on the period after felling, by analyzing the recovery of carbon sink capacity and also the evolution of annual and seasonal patterns GPP, tree growth and evapotranspiration. The main working hypothesis was whether our eddy covariance and meteorological data corroborated available information about *Eucalypt Globulus* Labill, obtained by allometric, physiological and hydrological studies, allowing thereby improvement for coordination of future scientific strategies in addressing such complex and challenging issues.

2 Material and methods

The experimentation on carbon sequestration in the eucalypt stand in Herdade da Espirra was part of the Carboeuroflux and Carboeurope projects. The site is located in a 300ha eucalypt (*Eucalyptus globulus* Labill.) in the county of Pegões (38º38’N, 8º36'W) in Southern Portugal. The stand is located in a flat area intensively managed as a coppice for pulp production, with a density 1100 trees/ha and a 12 month growth period. The climate is Mediterranean type with mean annual temperature and precipitation over the long term (1961–1990) of 15,9ºC and 709mm respectively. Under normal conditions the precipitation occurs mainly between October and April, with no rainfall in summer. A tree felling was made in October-November 2006 after a twelve year productive cycle in trees with 20m average height. The young shoots were submitted to a cultural thinning in October–December 2008, for the removal of three stems of each group of four stems per stump. The new trees showed strong height growth reaching an average 8m height in December 2010 and were also sensitive to winter frost after 2007 inducing leaf yellowing and death.

An average total biomass of 123 ton ha^{-1} was estimated at the end of rotation, with an annual increment of *circa* 19 ton year^{-1} in 2002-2003, dropping to 7,8 ton year^{-1} in the dry period 2005-2006. After the trees felling in an area of 200 ha, an average 13,6 ton biomass ha^{-1} of litter(leaves, branches and twigs) was left in the soil (Rodrigues et al. 2011). Data for belowground carbon was estimated as 38,2t/ha of carbon remained in soil till 1m depth, corresponding to 15t/ha, 12,4t/ha and 10,8t/ha in the 0-25cm, 25-60cm and 60-100cm soil layers, respectively.

Carbon flux and evapotranspiration measurements were made by eddy covariance (Aubinet et al. 2000) at a 21 Hz data sampling rate with an experimental unit installed in 2002 at the top of a 33m watch tower but moved to a 12m height after the felling. The instrumentation included an ultrasonic Gill, R2 anemometer, an open path IRGA LI-7500 gas analyzer and an automatic weather station (Campbell Scientific CR10 data-logger) for continuously monitoring the main meteorological parameters. Subsequently, after the felling, the eddy covariance unit was moved to a height of 12m above the ground. The distance

from the tower to the edge of the stand varied between 700m 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 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) Instantaneous data with friction velocity below 0,2 ms^{-1}, mean vertical velocity fluctuations higher than

0,35 ms^{-1},high frequency and low frequency spikes(Papale, 2006) were discarded. Gap-fillin of missing or bad quality data and a partition of carbon uptake in gross primary production and total respiration (Reichstein et al. 2005) was made with an online algorithm (http://gaia.agraria.unitus.it/database/eddyproc/). An automatic weather station (Campbell Scientific CR10 data logger) was installed to sample meteorological data every 30s and recording averages 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, 29.2m and 31.6m with self produced Cu-Cons thermocouples of 0.15mm diameter. Global incident radiation and net radiation were also measured. For additional details on methodologies of fluxes and meteorological measurements refer to Rodrigues et al., 2005 and Rodrigues et al., 2011. Leaf area index was obtained from MODIS satellite data. Soil carbon storage was evaluated before(2002) and after the felling(2007) by excavation in four points close to watch tower with four replicates at depths 0-25cm, 25-60cm and 60-100cm. Soil samples were oven-dried and total carbon was evaluated by the method described in ISO standard 10694.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 $225m^2$ adjacent to the tower, for allometric estimation of total carbon biomass. The equations used were these reported by António et al. (2007) for individual trees.

The values of moisture and soil temperature were measured continuously for periods of two hours from January 2007 at depths of 10 cm, 20,cm, 30 cm, 40 cm, 60cm and 1m with a Delta-T probe, model PR2.

3 Results and discussion

3.1 Meteorological variables

The annual results of accumulated NEE, GPP, TER, precipitation (Prec) evapotranspiration (mm) and global solar radiation (*R*g) and mean air temperature are shown in Table 1. The average temperatures in 2003, 2004, 2005, 2006, 2009 and 2010 exceeded the long-term average of 15,9ºC. The annual rainfall in 2004 and 2005 was reduced by 47% compared to the long-term average of 709mm. (Fig. 1).Throughout the period covered by this study, accumulated rainfall during June–September was less than 9% of total precipitation. The drought years of 2004 and 2005, besides the lower rainfall, showed a marked asymmetry in the distribution of rainfall throughout the year. Indeed the precipitation occurred in the first quarter of 2004 accounted for 55,5% of total annual and in 2005 the accumulated rainfall in the last quarter represented 40% of the annual total.

The highest values of average monthly atmospheric vapor pressure deficit (VPD) in the two drought years were 7,56 hPa and 8,67 hPa respectively. Monthly average VPD decreased to 5,34 hPa in the period after tree cutting. Precipitation after the felling increased to 443,05 mm, 508,81mm 571,8mm and 959,2 mm, in 2007, 2008, 2009 and 2010, respectively. Over the whole years incident solar radiation and temperature showed a relatively steady variation, not comparable to seasonal and annual variations of precipitation in dry years. In 2007–2010 soil moisture increased annually with depth between 3,4% at 10 cm and 11,4% at 1 m, surpassing wilting point in sandy soils (5%) below 60 cm. Soil moisture depth showed also averaged monthly variation between 5% in August–October and 11% in November-February.

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3.2 Carbon fluxes

The impact on GPP derived from the drastic reduction of precipitation in 2004 and 2005 was felt mainly in 2005. Indeed, the values of GPP were respectively 2206,0 gCm^{-2}, 1995,3 gCm^{-2}, 1834,8 gCm^{-2}, and (Table 1 and Fig. 2) in 2002, 2003 and 2004 respectively, dropping to 1255,1 gCm^{-2} in 2005 (Table 1). In 2004, the first drought, year the annual rainfall of 396,6mm almost nearly the total evapotranspiration of 722,5mm, depleting soil water and sustaining values of GPP to levels of the same order of 2002 and 2003. This agrees with the general principle applied to some eucalypt species that when atmospheric evaporative demand is high and trees still have water reserves in the soil, high rates of evapotranspiration can occur (Newson and Calder, 1989, Greenwood et al. 1985). In the period prior to felling the average monthly NEE and GPP were maximum in the middle spring and minimum in late summer (Fig. 3). Its variation was opposite to VPD deficit, with the September fall in carbon uptake coinciding with maximum monthly VPD. This is due to the fact that forest stomatal conductance tends to be higher at low VPDs, as shown, e.g., by David et al. (1997) for eucalypt stand in Portugal. The maxima of NEE and GPP 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 5 mid-March, with decreasing latitude. The values of leaf area index (LAI) obtained by remote sensing from MODIS

satellite varied seasonally around 5 in the period before the felling. Averaged monthly LAI decreased in 2005 due to leaf yellowing associated with intense water stress.
After the felling in October–November 2006 the eucalypt coppice, deprived of foliage, become a carbon source.
New shoots emerged from the remaining stumps and the stand recovered its capacity carbon sink after June 2007 with annual GPP of 1226 gCm^{-2}, 1294.1 gCm^{-2}, and 1621.6 gCm^{-2} in 2008, 2009 and 2010, respectively (Table 1). Typical day curves of GPP on a quarterly basis in averaged periods 2002–2003 and 2009–2010, reflect the tendencies of monthly GPP. Indeed in Fig. 4B it is shown that in the averaged period 2009–2010, mean daily GPP was higher in July-September than in winter. Oppositely, in the averaged period 2002–2003 (Fig. 4a) GPP values were higher in all quarters and in winter GPP was significant and higher than in summer. On the other hand, in 2002–2003 as a consequence of water stress summer GPP showed an asymmetrical pattern at noon much more obvious than in 2009–2010.
Typical day curves in the whole 2002–2010 period (not shown) indicated that as rule global solar radiation phased and peaked with NEE and GPP at about noon and TER phased with VPD and air temperature (Rodrigues et al., 2011). Typical day curves of evapotranspiration and GPP were also synchronized showing the fundamental role of leaf stomata on the linking of carbon and water fluxes.
The annual averaged values of MODIS LAI of young plants increased to 2,4, 3,4, 2,8 and 3,1 in 2007, 2008, 2009 and 2010 respectively, reflecting a lower aerial biomass, comparatively to the period before the felling. Mean LAI in 2008 was reduced by the thinning in the last quarter. Anyway this significant LAI growing is associated to a fast growth in the young plants up an average 8m height at the end of 2010.Young plants were sensitive to the effects of winter frost in the four years after cutting, with crisp leaf yellowing processes.
The fast regeneration of the eucalypt stand agrees with allometric data of Soares et al 2007 and with the aforementioned conclusions of hydrological studies about the maintenance of a mature and viable root system (David et al .1994, Fernández et al. 2006) able to extract water at deeper levels with higher soil moisture. Thereby the new plants with a reduced aerial biomass and a developed root system were able to withstand summer water stress and assimilating carbon in summer under higher solar radiation. The monthly pattern of GPP in 2008 and 2009(Fig. 3) was thus changed, almost reversed peaking in summer when higher solar radiation is available, without the

leaf stomata control typical of mature trees with higher aerial biomass under high water stress. On the other hand, GPP in these years decreased in winter, especially in January, due to the thinning in October-December 2008 and to a higher sensibility to frost. In 2010, despite a falling in winter, monthly GPP peaked at late spring (Fig. 3) almost coinciding with the corresponding maximum in 2002–2003. Thereby it is expected that the pattern change of seasonality should be temporary and abolished as the aerial biomass of the new trees increases. This agrees with conclusions of hydrological and physiological studies (Osório et al., 1998) pointing to the fact that an increase in leaf production in eucalypt diminishes resistance to water stress inducing thereby the stomata leaf response control to water stresses.

4 Conclusions

The eucalyptus coppice submitted to intensive management was as a substantial carbon sink with NEE and GPP of about -791 gCm^{-2} and 2000 gCm^{-2} in the period 2002–2004, when the effects of lack of precipitation were not felt. GPP diminished after the felling and GPP monthly pattern also changed, especially in 2008–2009 with higher carbon assimilation in summer, oppositely to period before the felling when summer carbon uptake practically stopped.

The results of eddy covariance methodology reinforced the hypothesis made under hydrological, allometric and physiological studies whereby the maintenance of a mature root system in a coppiced eucalypt stand is crucial to guarantee a fast growing of young plants. Indeed, not only GPP increased significantly during the four year period after felling, accompanying the strong tree height growth, but also carbon assimilation in summer was possible in 2008 and 2009, given the imbalance between aerial and root biomass. This profile tendency proofed as transient till 2010, when supposedly trees begun to achieve maturity and the stand began to invert to the situation prior to the felling.

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