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Recovery of GPP monthly pattern in a eucalypt site in Portugal after felling

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Abstract

The main objective of this work was to report the recovery of seasonal pattern of GPP obtained by eddy covariance measurements in a eucalypt *(Eucalyptus globulus Labill.)* site in Pegões (Southern Portugal) after a felling processed in October and November of 2006. This was made in a wider context of a general description of the evolution of carbon sequestration at several timescales in the period 2002–2010. In Portugal eucalypt stands aimed mainly for pulp production occupies an area of about 739 515 ha, (National Forest Inv 2005–2006) corresponding to about 23% of total forest area. The site is part of a 300 ha eucalypt stand, located in Herdade da Espirra, intensively managed as coppice under a twelve year productive cycle with a density of about 1100 trees/ha and characterized by a 12-month growing period. A prolonged drought in 2004 and 2005 and a felling in October–November 2006, followed by the start of a new production cycle, changed the carbon sink ability of eucalypt stand. In the two drought years, rainfall was reduced to values of 50%, relatively to long-term 709 mm average of. In the period prior to cutting NEE of 8.7 g cm^{-2} was maximum in 2002 decreasing to a minimum of 3.6 tons/ha in 2005 at the peak of the effect of drought. After the felling the eucalypt stand recovered its carbon sink capacity in June 2007 with an annual GPP of 1621.6 g cm^{-2} in 2010. Seasonal patterns of GPP in 2007, 2008 and 2009 were almost opposite to that of the period before the felling, with a tendency to recover to the situation prior the felling in 2010.

1 Introduction

In the current context of climate change forest ecosystems become important agents of carbon sequestration. 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. The concentration of atmospheric CO_2 increased from about 280 ppm in the early days of the Industrial

Revolution to the present value of the order of 370 ppm, corresponding to global emissions of 7 billion tons, half of which are retained in the atmosphere. In turn, the average increase in air temperature in Europe was approximately 0.95 °C at the surface (IPCC, 2001), succeeding that eleven of the warmest years between 1860 and 2006 occurred during the 12 years prior to 2006 (Espirito Santo, 2006). In Portugal, since 1975, the temperature increase has occurred at a rate of 0.5 °C per decade. The estimated value for the abstraction of carbon dioxide for European forests is the 0.205 PgC/ano 0135, amounting to 7–12% of emissions in 1995 (Janssens et al., 2001). The Kyoto Protocol of 1997, established that industrialized countries should reduce their emissions between 2008–2012 to levels of 5.2% lower than the values observed in 1990. Therefore, the various countries need to quantify carbon sequestration in their forests. In Portugal, eucalypt is a forest specie under intensive management aimed primarily for pulp production, with high wood productivity of about 16 m^3 ha^{-1} $year^{-1}$, occupying an area of about 739 515 ha or about 23% of total forest area (National Forest Inv 2005–2006). In the Mediterranean region 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 Portugal was the most severe of the last 140 years (Garcia-Herrera et al., 2007). Over the past 20 years the scientific knowledge on the factors affecting NEE, GPP and TER in forests improved substantially, due to research programmes such as Carboeuroflux (2000–2003), Carboeurope (2004–2008) or networks such as Fluxnet. Among these factors are these linked to weather, latitude, (Valentini et al. 2000) season of the year (Falge et al., 2002), tree biology, leaf area index, duration of the growing season or temperature and soil moisture (Schmidt et al. 2000). Particularly, 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 vapour deficit and photosynthetic active radiation may by obtained e.g. by general estimating

BGD
8, 3999–4014, 2011

equations modelling (Rodrigues et al., 2011).

During the 2002–2010 period, 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. Seasonal pattern of GPP following the felling was also almost opposite in the period 2007-2009, comparatively to the period prior the felling. In 2010 a tendency for recovering of the former seasonal pattern prevailed.

In all this context, it was intended in this study to evaluate the potential for carbon sequestration in the eucalypt plantation in this nine year period, considering the impact of these two events, and giving special attention to carbon sink patterns at daily, seasonal and annual timescales.

2 Material and methods

The experimentation on carbon sequestration in the eucalypt stand in Herdade da Espirra was part of the aforementioned Carboeuroflux and Carboeurope projects. The site is located in a 300ha eucalypt (*Eucalyptus globulus* L.) in the county of Pegões (38°38′ N, 8°36′ 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 15.9 °C and 709 mm respectively. Under normal conditions the precipitation occurs mainly between October and April, with no rainfall in summer. A tree felling was made in October 2006 under a twelve year productive cycle in trees with 20 m average height. The young shoots of the coppice were submitted to a cultural thinning in October–December 2008, for the removal of three stems of each group of four stems per stump. In 2010, an organic fertilizing was made in order to increase soil organic matter. The new trees were also sensitive to winter frost after 2007 inducing leaf yellowing and death. The new trees averaged 8 m height in December 2010.

BGD
8, 3999–4014, 2011

Carbon flux and evapotranspiration measurements were made by eddy covariance (Aubinet et al. 2000) with an experimental unit installed in 2002 at the top of a 33 m observation tower but moved to a 12 m height after the felling. The instrumentation included an ultrasonic Gill, R2 anemometer, a open path IRGA LI-7500 gas analyzer and an automatic weather station (Campbell Scientific CR10 data-logger) for continuously monitoring the main meteorological parameters. A partition of carbon uptake in gross primary production and total respiration (Reichstein et al. 2005) was made by gap filling online algorithm (http://gaia.agraria.unitus.it/database/eddyproc/). For 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. 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, 60 cm and 1 m 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 and 2009 exceeded the long-term average of 15.9 °C. The annual rainfall in 2004, 2005, 2007, 2008 and 2009 was reduced by 47%, 44%, 37%, 29 % and 20% compared to the long-term average of 709 mm (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.

BGD
8, 3999–4014, 2011

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 slightly to 443.05 mm, 508.81 mm 571.8 mm and 959.2 mm, in 2007, 2008, 2009 and 2010, respectively. Over the years covered by this study, the 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 3.47% at 10 cm and 11.49% at 1 m, surpassing wilting point in sandy soils (5%) below 60 cm. Soil moisture depth averaged showed also monthly variation between 5% in August–October and 11% in November-February.

3.2 Carbon fluxes

The impact on carbon balance, gross assimilation and respiration, derived from the drastic reduction of precipitation in 2004 and 2005 was felt mainly in 2005. Indeed, the values of the NEE were −865.56 g cm^{-2} in 2002, −791.33 g cm^{-2} in 2003, −724.24 g cm^{-2} in 2004 dropping to −356.64 gcm^{-2} in 2005, the second year of drought in which the annual rainfall was 396.64 mm (Table 1).The corresponding figures for GPP in 2002, 2003, 2004 and 2005 were respectively 2206.04 g cm^{-2}, 1995.35 g cm^{-2}, 1834.88 g cm^{-2}, and 1255.11 g cm^{-2} (Table 1 and Fig. 2). In 2004, the first drought, year the annual rainfall of 396.64 mm almost nearly the total evapotranspiration of 722.55mm, depleting soil water and sustaining values of NEE (−724.24 g cm^{-2}) and GPP (1834.88 g cm^{-2}) to levels of the same order of to these of 2002 and 2003. During 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 maxima 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 Eucalyptus globulus in Portugal. In Mediterranean ecosystems the role of stomata in controlling atmospheric

BGD
8, 3999–4014, 2011

gas exchanges under summer conditions of higher air temperatures and VPD is the main cause for the decrease of carbon assimilation in summer. 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 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.

In 2006 with slightly higher levels of precipitation (360 mm in the period before the felling) the eucalyptus trees regained their ability to carbon sink with an annual NEE and GPP of −619.07 g cm^{-2} and 1816.66 g cm^{-2} respectively. 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 g cm^{-2}, 1294.1 g cm^{-2}, and 1621.6 g cm^{-2} in 2008, 2009 and 2010, respectively (Table 1). In the same period the corresponding values of annual NEE were −200.73 g cm^{-2}, −208.6 g cm^{-2}, and −95.8 g cm^{-2} respectively. The annual values of MODIS LAI of young plants also declined 2.41, 3.46, 2.8 and 3.1 in 2007, 2008, 2009 and 2010 respectively, reflecting a lower aerial biomass. Mean LAI in 2008 was reduced by the thinning in the last quarter. The decrease in NEE in 2010 (Table 1), was associated to an increase in TER due to the organic fertilization and to high levels of monthly precipitation in winter and spring 2010 (annual total of 959.2 mm) promoting heterotrophic microbial respiration in soil.

Despite the carbon uptake, overall values of NEE and GPP after the felling were still lower than these before the felling (Table 1, Fig. 2) indicating that the eucalypt stand in still recovering its full carbon sink potential.

Monthly pattern of the GPP in 2008 and 2009 was almost opposite to that of the eucalypt stand at the end of their productive cycle (Fig. 3), with maximum GPP values in late summer and minimum in winter. The main explanation for this monthly lag is related to the fact that after felling the deep roots remained intact and available to the stumps and emerging shoots. Thereby the new plants with a reduced aerial biomass improved their capacity to extract water at deeper levels with higher soil moisture in summer 2008 and 2009, withstanding summer water stress and assimilating carbon under higher solar radiation. 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 is expected that the pattern change of seasonality should be temporary and abolished as the aerial biomass of the new trees increases. Water stress during periods of summer after the felling was also minimized either by a more uniform distribution of precipitation in 2008 and 2009 simultaneous with monthly atmospheric VPD. The young plants that reached heights of 8m at the end of 2010, were too sensitive to the effects of winter frost in the four years after cutting, with crisp leaf yellowing processes.

Typical day curves of GPP on a quarterly basis in averaged periods 2002–2003 and 2009–2010, reflect the aforementioned tendencies of monthly GPP. Indeed Fig. 4B shows that in the averaged period 2009–2010, mean daily GPP was higher in July-September comparatively to winter months. 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). In the same period typical day curves of evapotranspiration and GPP were also synchronized showing the fundamental rule of leaf stomata on the linking of carbon and water fluxes.

BGD
8, 3999–4014, 2011

4 Conclusions

The eucalyptus coppice submitted to intensive management was as a substantial carbon sink with NEE and GPP of about 791 g cm^{-2} and 2000 g cm^{-2} in 2002–2004, respectively, years when the effects of lack of precipitation were not felt. NEE and GPP diminished substantially after the felling. Monthly pattern of GPP also changed, especially in 2008–2009 with higher carbon assimilation in summer, oppositely to period before the felling when summer carbon uptake practically stopped. This tendency was certainly transient as it began to invert in 2010 to the situation prior to the felling.

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BGD
8, 3999–4014, 2011

Recovery of GPP monthly pattern after felling

A. Rodrigues and G. Pita

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BGD

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Recovery of GPP monthly pattern after felling

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Table 1. Cumulative totals of NEE GPP and TER, mean air temperature $(T_a)_a$, global solar radiation, $(R_g)_g$ rainfall (Prec), and evapotranspiration (E).

Annual	T_a (°C)	R_g(MJ m^{-2})	Prec (mm)	NEE (gCm^{-2})	GPP (gCm^{-2})	TER (gCm^{-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	16.57	6243.81	571.8	−209.01	1294.45	1086.44	560.77
2010	16.39	5967.00	959.20	−95.8	1621.6	1525.6	1113.41

BGD
8, 3999–4014, 2011

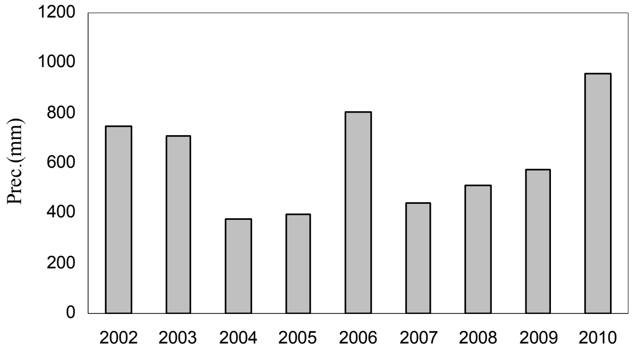

Fig. 1. Evolution of annual precipitation in the whole period.

BGD
8, 3999–4014, 2011

Recovery of GPP monthly pattern after felling

A. Rodrigues and G. Pita

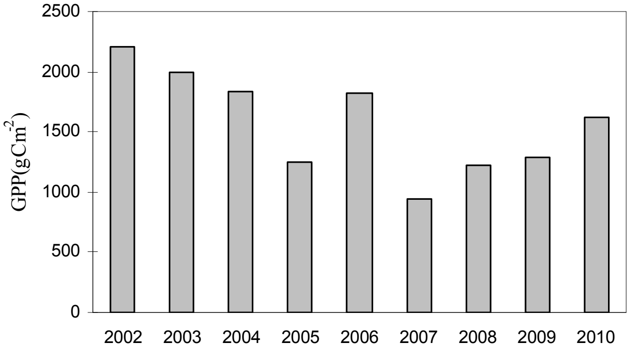

Fig. 2. Annual GPP for the whole period.

BGD

8, 3999–4014, 2011

Recovery of GPP monthly pattern after felling

A. Rodrigues and G. Pita

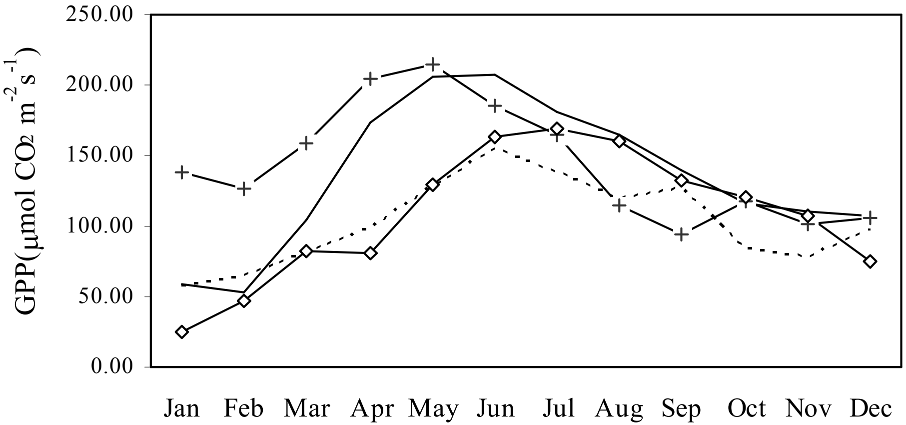

Fig. 3. Monthly average GPP (+ avg. 2003–2006, – – – 2008, ◊ 2009, —— 2010).

BGD
8, 3999–4014, 2011

A. Rodrigues and G. Pita

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

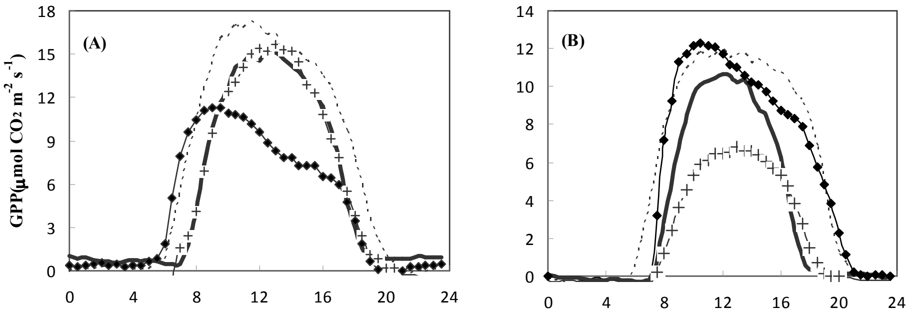

Fig. 4. Typical day curves for average GPP: **(A)** avr. 2002–2003, **(B)** avr. (2009–2010) (+ Januar–March, – – – April–June, ♦ July–September, ▬ October–December).

BGD

8, 3999–4014, 2011

Recovery of GPP monthly pattern after felling

A. Rodrigues and G. Pita