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# Reversing of seasonal patterns of carbon uptake in an eucalyptus stand in Portugal after drought and felling

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## Abstract

This paper summarizes results between 2002 and 2010 from eddy covariance measurements of carbon uptake in the 12 month annual growing period eucalypt site of Espirra in Southern Portugal (38° 38' N, 8° 36' W) . This site, aimed for pulp production is part of an intensively 300 ha eucalypt coppice, with about 1100 trees $ha^{-1}$. The climate is of Mediterranean type. During the measurement period (2002-2010) two main events changed the annual sink pattern of the forest: a drought period of two years (2004-2005) and a tree felling (November and December 2006). Before the felling, annual net ecosystem exchange (NEE) diminished from 865.56 $gCm^{-2}$ in 2002 to 356.64 $gCm^{-2}$ 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. The eucalypt stand recovered its carbon sink ability in June 2007 with a cumulated NEE of 151 $gCm^{-2}$ from January to September 2010. A quantitative approach using generalized estimating equations (GEEs) was made to relate monthly NEE, gross primary production (GPP) and soil moisture with the main meteorological variables. Seasonal patterns of carbon uptake were almost opposite in the periods before and after the felling with maxima in April and August, respectively, and this seasonal change is gradually reversing to the pattern before 2006. Drought was the main meteorological driver of these temporal tendencies in carbon uptake.

**Key words**: drought; carbon; tree felling; water stress; GEEs.

## Resumen

### Inversión de los patrones estacionales de la absorción de carbono en un stand de eucalipto en Portugal después de la sequía y la tala

Este documento resume los resultados entre 2002 y 2010 a partir de mediciones de covarianza turbulenta de la absorción de carbono en los 12 meses anuales a los sitios de crecimiento de eucalipto período de Espirra en el sur de Portugal (38° 38' N, 8° 36' W). Este sitio, con el objetivo para la producción de celulosa es parte de un monte bajo de intensidad 300 hectáreas de eucaliptos, con cerca de 1.100 árboles $ha^{-1}$. El clima es de tipo mediterráneo. Durante el período de medición (2002-2010) dos eventos principales cambiado el patrón fregadero anual de la selva: un período de sequía de dos años (2004-2005) y la tala de árboles (noviembre y diciembre de 2006). Antes de la tala, el intercambio anual neta de los ecosistemas (NEE) se redujo de 865,56 g $cm^{-2}$ en 2002 a 356,64 g $cm^{-2}$ en 2005, junto con una disminución profunda de las precipitaciones de 748 mm en 2002 a 378,58 mm y 396,64 en 2004 y 2005, respectivamente. El eucalipto de pie recupera su capacidad de sumidero de carbono en junio de 2007 con un acumulado de 151 gcm $NEE^{-2}$ de enero a septiembre de 2010.Una aproximación cuantitativa mediante ecuaciones de estimación generalizada (GEES) se hizo para relacionar mensual NEE, la producción primaria bruta (GPP) y la humedad del suelo con las variables meteorológicas principales.Los patrones estacionales de la absorción de carbono eran casi opuestas en los períodos antes y después de la tala, con máximos en abril y agosto, respectivamente, y este cambio de temporada se va de marcha atrás para el patrón antes de 2006. La sequía fue el principal impulsor de estas tendencias meteorológicas temporal en la absorción de carbono.

**Palabras clave**: sequía; de carbono, la tala de s; stress hídrico; GEEs.

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# Introduction

Portuguese forest area covers 37% of the national territory (3 million hectares) with intensively managed eucalyptus forests used for pulp production corresponding to about 19% of that area. These eucalypt forests are highly productive with 16 $m^3$ $ha^{-1}$ $year^{-1}$ of wood in a relatively short productive of 12 years. Pulp and paper industrial cluster is the main forest industry in Portugal, corresponding in 2001 to about 11% of total investment in the country and 5.4% of total exports. The main export destinations of pulp and paper products are EU countries traditionally importers of forests products

This work aimed to study the temporal variation of atmospheric carbon fluxes measured by eddy covariance from 2002 till 2010 in a eucalyptus site intensively managed as a coppice for pulp production, located in Southern Portugal. The plantation was established in 1986, and in 2002 a meteorological tower, 32 m high, was installed with the eddy correlation measurement equipment. In Mediterranean climates under dry summer conditions the carbon uptake by plants is mainly influenced by soil and atmospheric water conditions and regulated by stomatal control (Baldocchi, 1997; Reichstein *et al.,* 2002; Granier *et al.*, 2007; Pereira *et al.*, 2007).

In the nine year period considered two main events happened, drought in 2004 and 2005 and tree felling in 2006, with significant impact in annual and seasonal carbon uptake. In this context the main objectives addressed were the analysis of annual and seasonal evolution of carbon fluxes under the two main events and the quantification of relationships between meteorological variables and carbon uptake and assimilation

# Material and methods

## Site description

The experimental site is in a 300 hectare eucalypt (*Eucalyptus globulus* Labill.) plantation (38° 38' N, 8° 36' W), extending from 700 m to 1,800 m on a flat terrain and intensively managed as a coppice for pulp production. The soil is a Dystric Cambisol with a mean depth of 1.3 m. The climate of our study's area is typically Mediterranean characterized by discrete rainy periods mainly from October till April and without rainfall in summer (Miranda *et al.*, 2002), with a long term average (1961-1990) precipitation of 709 mm and a mean annual temperature of 15.9°C. In October 2006 a felling was made to the 12 year trees with an average 20 m height and trees spacing $3 \times 3$ meter. After felling, coppice sprouting regenerated the canopy. The new stems reached 1 m height after six months and 6 m after one year,. In the end of 2007 air temperature fell below 0°C at night for a few days and the young juvenile leaves were severely damaged by frost. A thinning of sprouts was made in October and November 2008 to maintain a single stem per stump.

## Instrumentation and calculations

The eddy covariance unit was installed in 2002 at the top of a 33 m tower and was comprised by 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 1,800 m. Half hour flux calculations involved two axis coordinate rotation, linear detrending, 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 minute 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 lab made 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, photosynthetic active radiation (PAR), and net radiation were also measured at the top of the tower. For additional equipment and correction descriptions refer to Rodrigues *et al.* (2005). Soil moisture data were continuously recorded with a probe Delta-T, Model PR2 every two hours since January 2007 at depths 10 cm, 20 cm, 30 cm, 40 cm, 60 cm and 1 m. LAI was estimated in monthly bases from MODIS algorithm.

The reported 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 covariance, a filtering removed data fluxes corresponding to *(i)* deviations of mean vertical velocity from zero greater than 0.35 ms$^{-1}$, *(ii)* high frequency spikes affecting single instantaneous measurements in a percentage above 1% and *(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). Data with friction velocity below the threshold of 0.2 ms$^{-1}$ were also discarded (Mateus *et al.*, 2006). Flux data remaining after this filtering process were submitted to stationarity and integral turbulence characteristics.

Gap filling and NEE partitioning in GPP, Gross Primary Production: rate at which an ecosystem's producers capture and store carbon as biomass, and Total Ecosystem Respiration (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).

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:

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

with $Y_i$ and $\mu_i$ corresponding, respectively, to the vectors of measurements and means in the $i$-th 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. [1] 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 Gibons, 2006).

## Results and discussion

### Meteorological conditions

The monthly mean values of precipitation before and after the felling are shown in Figure 1. In both cases, from June until September, four months in summer, the total amount of rain is very low, less than 9% of the annual precipitation.

During these dry months only the trees with roots that can reach humidity in deep levels in the soil can surviveas shown by the hydrological studies about the maintenance of a mature and viable root system (David *et al.*, 1994) able to extract water at deeper levels with higher soil moisture.

The cumulated values of precipitation, by hydrological years (starting in October) are shown in Figure 2. It's quite clear that there was a drought period, beginning in April 2004 until October 2005, with a total precipitation of only 290 mm, much lesser than 709 mm, the annual mean value from the last 20 years. After the

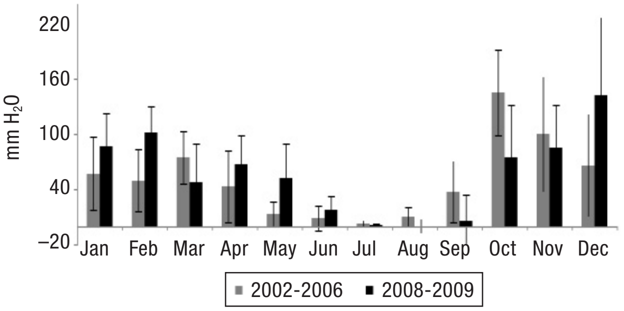

**Figure 1.** Monthly mean values of precipitation ±SD before (2002-06) and after felling (2007-09).

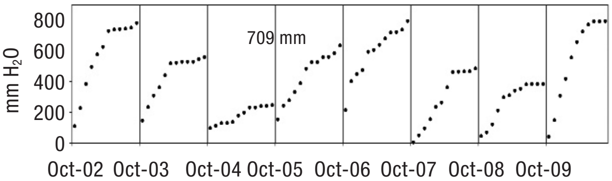

**Figure 2.** Cumulated values of precipitation in each hydrologic years (from oct-02 to aug-10). Horizontal line is the annual mean value from the last 20 years.

felling from Oct 08 until Sep 09 the total precipitation, 523 mm, was also much lower than the long term mean value. However in the autumn 2009 it has rained more than the usual.

## Carbon fluxes and GEE equations

Annual and seasonal patterns of carbon fluxes are shown in Figure 3. Mean annual carbon uptake (NEE) between 2002 and 2007 was 623 gCm$^{-2}$ with maxima in 2002 and 2003 of 866 gCm$^{-2}$ and 682 gCm$^{-2}$, respectively. Mean annual GPP for the same period was 1,746 gCm$^{-2}$ peaking also to 2,206 gCm$^{-2}$and 1,995 gCm$^{-2}$ in 2002 and 2003. After the felling, between 2008 and 2010 mean annual carbon uptake was 131 gCm$^{-2}$ and mean annual GPP for the same period was 1,210 gCm$^{-2}$.

The prolonged drought of 2004 and 2005 was the most severe in 140 years (García-Herrera *et al.*, 2007) with rainfall values of 379 mm and 392 mm, corresponding respectively to 54% and 56% of the long term precipitation mean, 30-year averages (1961-1990). The drought effects in carbon fluxes were felt mainly in 2005, with accumulated values of NEE (356 gCm$^{-2}$), GPP (1,255 gCm$^{-2}$) and TER (899gCm$^{-2}$). In 2004 soil water depletion by trees, reflected by a total evapotranspiration was 723 mm, of a twofold magnitude of the rainfall, sustained relatively high values of NEE (724 gCm$^{-2}$) and GPP (1,835 gCm$^{-2}$). In the years prior to the felling, monthly averaged NEE had a maximum in mid-spring and a minimum in late summer.

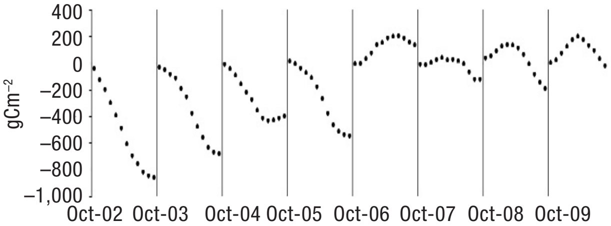

**Figure 3.** Cumulated values of NEE in each hydrologic year. (from oct-02 to aug-10).

After the felling the site without trees became a source of carbon. Six months after eucalypt stand recovered its sink capacity with higher carbon uptake in summer and minimum uptake in winter in the years 2007/08 and 2008/09. In these hydrologic years, carbon uptake was 123 gCm$^{-2}$ and 192 gCm$^{-2}$, respectively, with eucalypt plantation still recovering its full sink potential. Mean monthly NEE varied from 57.39 gCm$^{-2}$ (August) to 21.45 gCm$^{-2}$ (January) with a period of 233 days, from mid February till mid October showing carbon uptake (0 to –67.7 gCm$^{-2}$ mon$^{-1}$) following thereby a pattern almost opposite to trees in the term of their productive cycle.

Carbon uptake in Espirra is high comparatively to other sites of intensively managed forests in Europe. For example, a study from Granier *et al.* (2002) relative to two mature beech sites (Hesse in France and Sorø in Denmark) in a three year period indicate maximum annual NEE of 68 gCm$^{-2}$ to 296 gCm$^{-2}$ of the same order of magnitude of young Espirra eucalypt shoots in 2007 and 2008. On the other hand, the length of growing season and the pattern of seasonality of carbon uptake are also distinct. While in the Espirra site the growing period lasts all year with carbon uptake restricted in summer by water stress, in the beech sites the growing period continues for 149 and 157 days from mid-spring till end-summer. Pilegaard *et al.* (2001) report yearly accumulated GPP values for the same Danish beech site of 1,335 gCm$^{-2}$ and 1,271 gCm$^{-2}$ in two 12 month periods from 1996 to 1998, which are also smaller than the values of mature eucalypt trees of the Espirra site in the years 2002, 2003, 2004 and 2006.

In Figure 4 the LAI obtained from MODIS shows that before the felling its value is around 5, except at the end of the drought period when it fells to around 3. After the felling the LAI increases but in winter when during some nights temperature drops to values near 0°C, the young leaves from the new trees became frosted and the LAI diminishes. This decrease is obser-

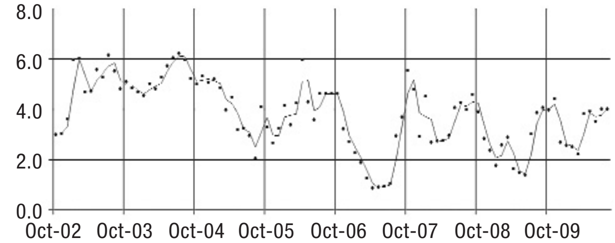

**Figure 4.** Leaf area index (LAI) from MODIS along all the period studied.

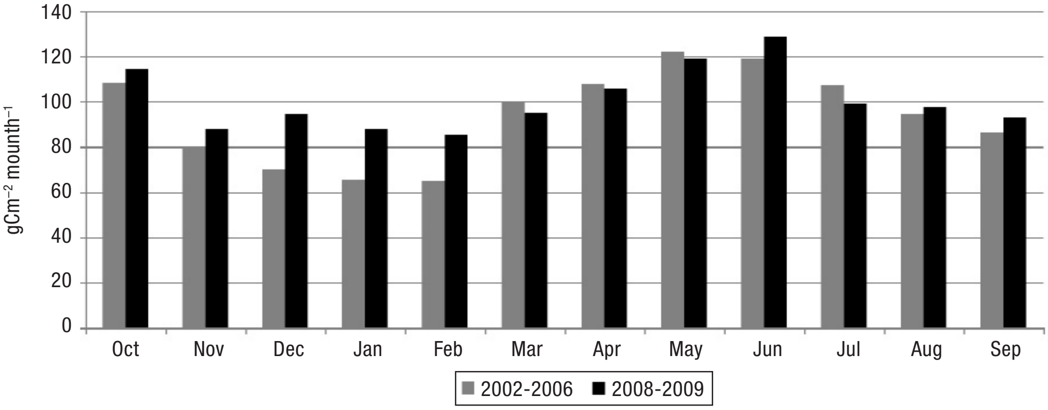

**Figure 5.** Monthly mean values of TER before (2002-06) and after (2008-09) the felling.

ved every winter after the felling, what causes the decrease in carbon uptake (Fig. 3).

Before the felling flux partion, mentioned above, indicated that TER (Fig. 5) was lower in winter (Nov-Feb) and starting to increase during spring, with a maximum value of 129 gC $m^{-2}$ May-Jun. After felling the annual is similar with the highests values of respiration in winter. These high values must be due to the decomposition of leaves and branches that were left in the field after the felling.

In October 2008 a first thinning was made in three fourths of emerging stems from stumps. The cut branches and leaves were also left over the soil contributing to increase the ecosystem respiration. At this stage the forest trees had a mean height of 6 m. The GPP before and after felling is plot in Figure 6.

The pattern of carbon assimilation by the forest plantation is different before and after the felling. Before the felling, in winter time, the photosynthetic activity of trees was limited by lower sunlight: probably by less hours of solar radiation and more clouds in the sky. In spring, with the increasing of daily solar radiation, GPP also increases, reaching a maximum value in April-May. In summer time, with the decreasing of soil water availability and increasing of Vapour Pressure Deficit (VPD) in the atmosphere, the gas exchanges at leaf level are controlled by stomatal closure and the GPP decreases until September when it reaches a minimum value Granier et all (2003). In October when rain season begins, GPP begins also to increase but is limited by low solar radiation available.

After the felling the pattern of carbon assimilation was almost opposite than before, with higher carbon uptake in summer and minimum uptake in winter in the years 2008 and 2009 (Fig. 3). The main reason for that probably was the fact that the young coppice inherited a deep root system from the mature trees that remained in the soil after the felling. This root system typical of mature trees, associated to a much lower aerial part and lower leaf surface allowed the young

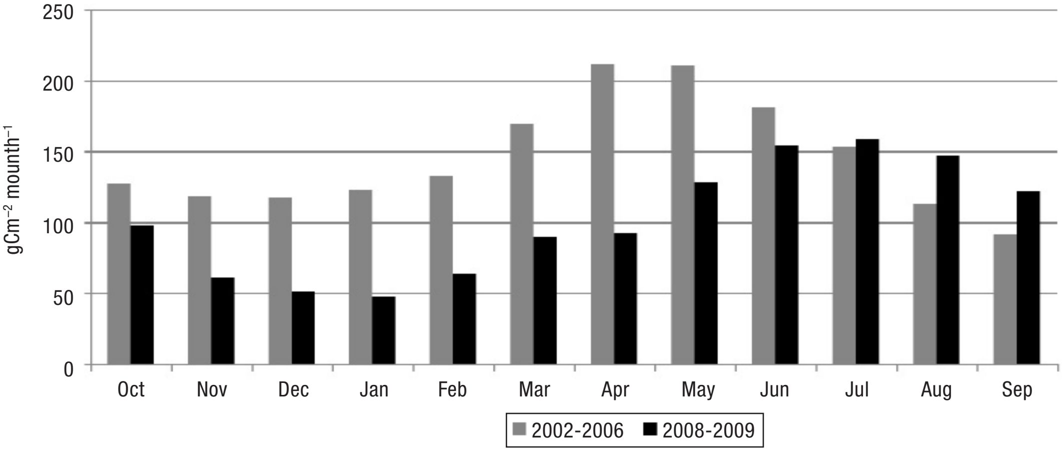

**Figure 6.** Monthly mean values of GPP before (2002) and after (2006) the felling.

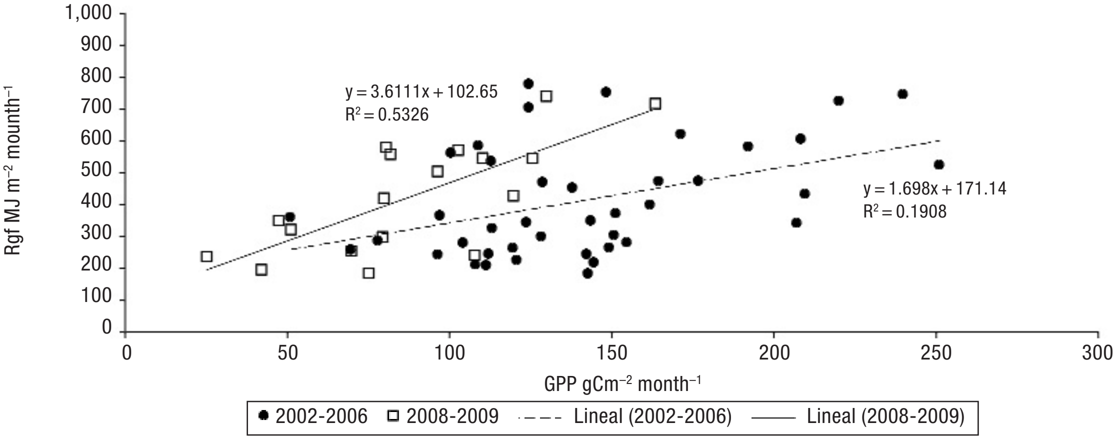

**Figure 7.** Relationships between GPP and monthly solar radiation (Rg), before and after the felling. Only the months with total precipitation above 10 mm where considered.

trees to withstand summer water deficit, under conditions of higher incident solar radiation.

After the felling in winter GPP decreased not only due to less solar radiation, but mainly due to the frost effect on the young leaves, decreasing the LAI. In spring new leaves grow and in summer LAI has reached maximum value with GPP also peaking. During the other months the GPP is limited by stomatal closure due to tree response to the water stress (values not plotted), Rodrigues *et al.* (2011)

The relationship between the GPP and solar radiation is shown in Figure 7. There was a good correlation during the months with total precipitation above 10 mm.

GEE equations were selected, relating monthly NEE and GPP to the main meteorological variables in the period before the felling considering identity link function and normal distribution. After an extensive analysis of distinct combinations of classification (month, year and month nested in year) and quantitative variables and working matrices and their coefficients of determination ($0.40 \leq R^2 \leq 0.49$) the chosen equations were:

$$\begin{aligned} \text{NEE(to)} &= -42.97 - 0.0903\ \text{PAR} + 0.0062\text{VPDac} \\ \text{PP(to)} &= 98.67 + 0.16\ \text{PAR} - 0.0085\ \text{VPDac} \\ \text{NEE(nst)} &= -42.04 - 0.12\ \text{PAR} + 0.0084\ \text{VPDac} \\ \text{GPP(nst)} &= 99.21 + 0.15\ \text{PAR} - 0.0066\ \text{VPDac} \\ \text{NEE(st)} &= 141.06 - 0.13\ \text{PAR} - 0.70\ \text{PR} \\ \text{GPP(st)} &= -225.036 + 0.26\ \text{PAR} + 2.02\ \text{PR} \end{aligned} \qquad [2]$$

where VPDac, PAR and PR are the accumulated monthly data of VPD (hPa), PAR radiation ($\text{MJm}^{-2}$) and precipitation (mm), and «to» means total monthly data, «st» water stress month (June till September), and «nst» no-stress month (other eight months).

Those equations are indicative of the combined influence of solar radiation and atmospheric water conditions (vapor pressure deficit and precipitation) in NEE and GPP, and are interesting under a practical point of view.

Proposed working matrices types for those equations were banded, 1-dependent [equations for GPP(to) and GPP(nst)], 2-dependent [equations for NEE(st) and GPP(st)], and autoregressive. This last type was selected only for equations for NEE(to) and NEE(nst). The classification variable considered in the selected models was the month. Statistics used to select the models were the similarity of empirical and model based covariance matrices, *z* scores and *p*-values for regression parameters, Table 1. The coefficients in all models were highly significant by the criteria of *p*-values to *z* scores. The elements of empirical and model based covariance matrices were of the same order of magnitude. Coefficients $R^2$ were evaluated after the GEE model selection. Those coefficients improved substantially relatively to the usual regression models.

## Soil moisture content

Soil water content has been measured continuously after the forest felling. Figure 8 shows the soil water content at three different depths (100 mm, 300 mm and 1,000 mm) measured with a Delta-T probe, Model PR2 along the 2009 year.

In order to select a GEE equation relating soil moisture content with atmospheric precipitation (P) and evapotranspiration (LE), from 2007 onwards, a preliminary regression study was made with SM and

**Table 1.** GEE models' statistics

| | **Confidence limits** | **Estimate** | **Standard error** | **pZscore** |
|---|---|---|---|---|
| *Model NEE(to)* | | | | |
| 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(to)* | | | | |
| 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 | $<0.0001$ |
| *Model NEE(nst)* | | | | |
| Intercept | –57.47, –26.604 | –42.0372 | 7.874 | $<0.0001$, $R^2=0.40$ |
| PAR coefficient | –0.1582, –0.0724 | –0.1153 | 0.0219 | $<0.0001$ |
| VPD coefficient | 0.0037, 0.0130 | 0.0084 | 0.0024 | 0.0005 |
| *Model GPP(nst)* | | | | |
| Intercept | 79.288, 119.1366 | 99.2123 | 10.1656 | $<0.0001$, $R^2=0.43$ |
| PAR coefficient | 0.117, 0.174 | 0.1455 | 0.0145 | $<0.0001$ |
| VPD coefficient | –0.011, –0,0021 | 0.0066 | 0.0023 | 0.0039 |
| *Model NEE(st)* | | | | |
| Intercept | 57.5795, 224.5384 | 141.059 | 42.5923 | $<0.0009$, $R^2=0.40$ |
| PAR coefficient | –0.1909, –0.0664 | –0.1286 | 0.0318 | $<0.0001$ |
| PR coefficient | –1.3211, –0.0873 | –0.7042 | 0.3147 | 0.0253 |
| *Model GPP(st)* | | | | |
| Intercept | 0.1307, 0.3857 | 0.2582 | 0.0651 | $<0.0001$, $R^2=0.44$ |
| PR coefficient | 0.7983, 3.2459 | 2.0221 | 0.6244 | 0.0012 |
| *Model SM* | | | | |
| Intercept | 0.9503, 4.1346 | 2.5425 | 0.8123 | 0.0017, $R^2=0.78$ |
| PLE coefficient | 0.4248, 0.6259 | 0.5253 | 0.0513 | $<0.0001$ |

the difference of P and LE as the as dependent variable and independent variables, respectively, considering periods of accumulated data of those two variables of two, four, eight and fifteen days. The accumulating period of eight days was chosen given the higher coefficient of determination (0.58) obtained. Subsequently an analysis of distinct combinations of classification (year, index T for eight day period and T nested in year) and working matrices was done, and the selected GEE equation, using the same criteria as for the carbon equations above, was:

$$SM = 2.54 + 0.52(P - LE) \qquad [3]$$

where SM is the accumulated soil moisture content over eight days in mm.The classification variable considered was the year and the corresponding working matrix was autoregressive. The selected GEE equation is plotted in Figure 9. The period of analysis correspond to the initial growing of young coppices (average LAI less than 3) and we assumed that the sequence of eight day period for water accumulation integrated also the effects of water interception by the canopy.

Soil water variations, measured (Fig. 8) as modelled by equation 2 (Fig. 9), in depth and time reflected thereby the continuous evolution of atmospheric water conditions. As mentioned above, young trees after 2007 due to a mature root system were able to resist to water stress in summer concomitantly with improved carbon assimilation due to the higher seasonal solar radiation.

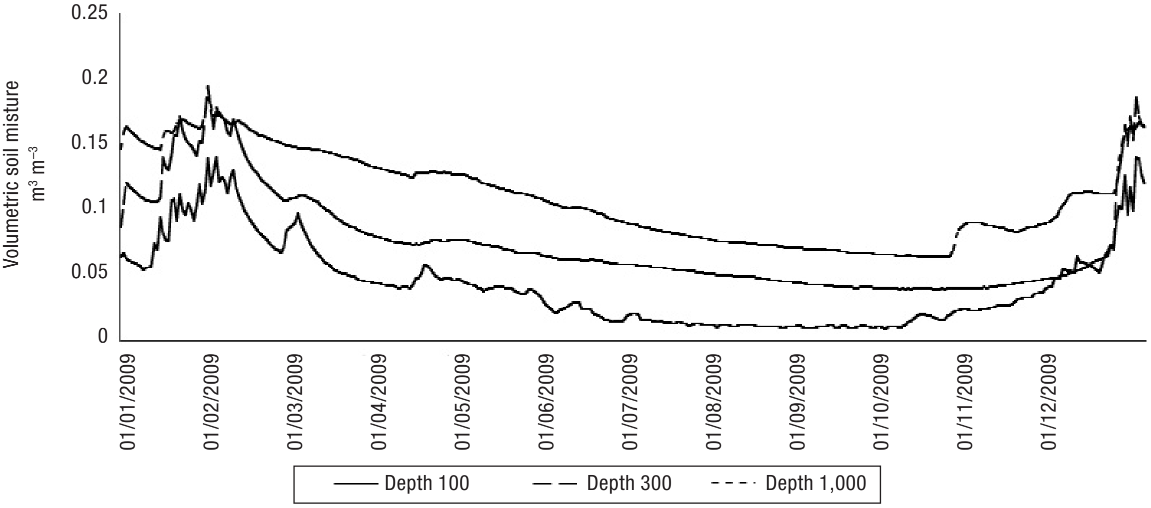

**Figure 8.** The day-to-day variation of volumetric soil moisture at three different depths (100 mm, 300 mm and 1,000 mm) in 2009.

## Conclusions

Intensively managed Eucalyptus Mediterranean stand in the second rotation cycle of 12 years was a strong carbon sink with maxima of almost 9 tons/ha, high comparing with other forests in Southern Portugal such as cork oak (about 0.6 tons/ha) or with other intensively managed forests in Europe.

For the adult forest carbon uptake had a seasonal pattern with maximum uptake occurring in beginning of spring (April), followed by a summer depression (June/July to September), period of higher stomata closure. The forest felling altered this pattern, with higher carbon uptake in summer, due to the effects of the matured root system inherited by stumps combined with a much lower aerial biomass, able to better withstand harsh summer water stress conditions. After the felling NEE decreased in winter due to low temperatures and winter frost inducing a decrease in LAI and a lesser GPP and higher TER.

The 2004/2005 prolonged drought was responsible for a substantial diminishing of 57% in the NEE from Jan. to Sep. 2005. In 2004, the first drought year (half the normal rainfall) eucalypt stand withstood the water stress due to root soil water depletion.

The dependence of carbon uptake and assimilation on meteorological variables, in the period before the felling, was established with GEE modeling. The selected equations showed that monthly NEE was mainly a function of solar radiation and water vapor deficit all over the yearly periods. In this period NEE and solar radiation clearly synchronized, excepting in the months from July to September, when, due to water stress, stomata closed inhibiting thereby foliar gas exchanges. This link between carbon and water vapour atmospheric exchanges in forest is a main issue in Mediterranean areas. Both interplay closely, determined by the tree stomatal control, in order to reduce water losses during dry hot summer months.

In the first six months after the felling the eucalypt stand was a carbon source. Thereafter TER had values similar as before, due to increased decomposition of leaves and branches left by the harvesting, and GPP was lower due to the smaller LAI of the young forest. NEE was thereby smaller than before the felling. The young coppice is still recovering its carbon sink capacity, with the low temperatures and frost determining a diminishing of LAI and carbon uptake in winter.

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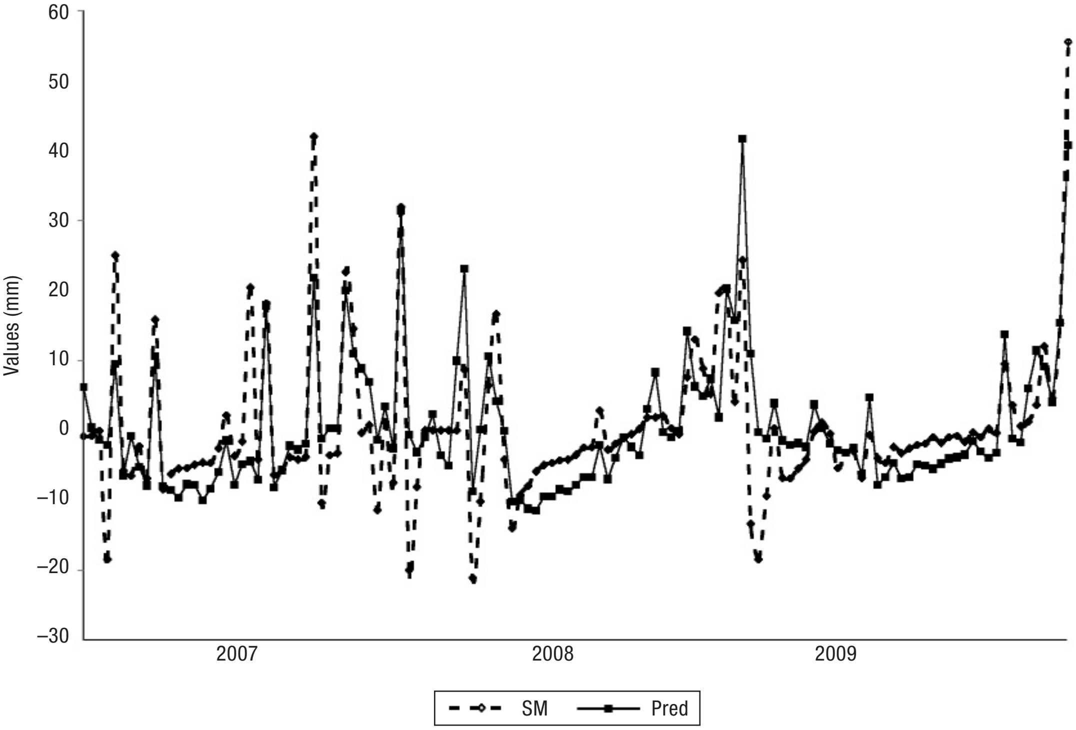

**Figure 9.** Measured (SM) and GEE fitted data (Pred) in the study period after felling,

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