

Turbulent Fluxes of Carbon Dioxide and Water Vapour Over an Eucalyptus Forest in Portugal

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Abstract. A twenty-two month campaign of turbulent flux measurements of CO₂ and water vapour was made, in order to contribute to the evaluation of the role of *Eucalyptus globulus* plantations in carbon sequestration. In this paper results of the fluxes are presented, considering its seasonal and daily variability. The mean yearly net ecosystem exchange was 8.9 tons Cha⁻¹yr⁻¹, with a Mediterranean forest year-long type assimilation, revealing that the plantation was a strong C sink. The data quality and results are compared with others obtained by the CARBOEUROFLUX network. A depression of carbon uptake occurred during summer, which is not a usual event in other sites but is probably due to stomatal closure associated with water vapor deficit and a peak in soil respiration.

Key words: fluxes; eucalypt plantation; carbon sequestration; seasonal cycles; evapotranspiration; data quality

Fluxos Turbulentos de Dióxido de Carbono e Vapor de Água em Floresta de Eucalipto em Portugal

Sumário. Para avaliação da capacidade de sequestro de carbono por plantações de eucalipto procedeu-se a uma campanha de vinte e dois meses, entre Fevereiro de 2002 e Dezembro de 2003, de medições de fluxos turbulentos de CO₂ e vapor de água. No presente artigo são apresentados os resultados desses fluxos, considerando a sua variabilidade sazonal e diária. O eucalipto funcionou como um sumidouro de carbono, com um balanço anual de trocas de carbono de 8.9 tons. Cha⁻¹, segundo um padrão de assimilação de tipo florestal mediterrâneo, com duração anual. A qualidade dos dados e os resultados foram comparados com informação obtida noutros locais experimentais da rede CARBOEUROFLUX. Verificou-se uma diminuição drástica da assimilação de carbono durante os meses de Verão, acontecimento não usual noutros locais experimentais, provavelmente em consequência de um encerramento dos estomas, associado a elevados défices de pressão de vapor e temperatura do ar e a um aumento da respiração do solo.

Palavras-chave: fluxos; eucalipto; sequestro de carbono; ciclos sazonais; evapotranspiração; qualidade dos dados

Flux Turbulents de Dioxyde de Carbone et de Vapeur d'Eau au-dessus d'une Forêt d'Eucalyptus au Portugal

Pour évaluer la capacité de séquestration du carbone par les plantations d'Eucalyptus, nous avons procédé à une campagne de vingt-deux mois, entre février 2002 et décembre 2003, effectuant des mesures de flux turbulents de CO₂ et vapeur d'eau. Dans cet article sont présentés les résultats de ces flux, tout en considérant la variabilité saisonnière et journalière. La plantation d'Eucalyptus a fonctionné comme un «réceptacle» de carbone, ayant comme balance annuelle d'échanges de carbone 8.9 tonnes.Cha⁻¹ selon un modèle d'assimilation de type forestier méditerranéen, de durée annuelle. La qualité des données et les résultats ont été comparés avec l'information obtenue en d'autres sites expérimentaux du réseau CARBOEUROFLUX. Une diminution drastique de l'assimilation de carbone a été vérifiée pendant les mois d'été, fait peu habituel dans les autres sites expérimentaux, probablement du à une fermeture des stomates, associée à des déficits élevés de pression de vapeur, à la température de l'air et à une augmentation de la respiration du sol.

Mots clés: flux; plantation d'Eucalyptus; séquestration de carbone; cycles saisonniers; évapotranspiration; qualité des données

Introduction

The study of the contribution of natural ecosystems to the global carbon cycle by fluxes associated to the physiological assimilatory and respiratory processes, is still in a incipient phase and constitute a major challenge to the scientific community. Particularly in European forestry, the importance of such a work is related to the need of optimizing the indicators of criteria for sustained management and as well to a better understanding, in the context of the Kyoto Protocol, of the mechanisms affecting the carbon sink role of temperate forests. Direct flux measurement is a useful methodology for improving the theoretical and empirical knowledge about the soil-plant-atmosphere relationships, allowing also a estimation of the impact of several forms of land use and management practices in carbon sequestration. A network of tower stations was thereby planned and installed at almost all the European countries in more than 30 sites, for a long term continuous monitoring of atmospheric exchanges of carbon dioxide and

water vapor by eddy covariance and of the associated energy budget components. The scientific European research projects EUROFLUX (1996-1999) and CARBOEUROFLUX (2000-2003) supported those actions. A vast range of factors associated to physical environment and life-forms are instrumental in modulating the carbon balance and determinant to the course and amount of gross primary production (GPP). Some of them are the seasonal variation of air meteorological conditions, leaf area index, physiological activity, length of growth season or soil temperature and moisture. The length of vegetative season, according to SCHMID *et al.*, 2000, during which photosynthesis is fully active, extends during a period during which soil temperature raises above a certain threshold, of about 13°C. The variability of the net ecosystem productivity (NEP) and of the net ecosystem exchange (NEE) are also major elements of carbon dynamics. Atmospheric fluxes of CO₂ provide a estimation of NEE, which differs from NEP in the amount of carbon exported from the system by run-off or harvest. GPP is

calculated as the summation of NEE and ecosystem respiration (RE), both in autotrophic (RA) and heterotrophic (RH) components. A main agent of RH in forests is the microbiological activity in soils, dependent of suitable physical conditions as well as of organic substrate availability and quality. As for RA, a continuous trend normally occurs, but with a degree of intensity depending on variables such as the actual stage and dynamics of stand growth, causing changes in the relative role of maintenance respiration. The environmental factors affect all those parameters differently. Whereas GPP is highly dominated by photosynthesis and controlled by photosynthetically active radiation (PAR), when air temperature is suitable for growth, RE relies more on air and soil temperature and moisture. The temporal course of net ecosystem exchange will depend of time phasing of those drivers, which affect distinctively GPP and RE, thereby establishing a delicate balance with distinct oscillatory diurnal, seasonal and annual patterns. The research programs above mentioned, already provided some highly relevant knowledge about the variability of carbon uptake with latitude (VALENTINI *et al.*, 2000) and season of the year, (FALGE *et al.*, 2002) as well as about interaction and influence of several physical and biological factors that affect those processes. A notorious optimization of methodologies was also achieved in equipment design and use, calculations and corrections of covariances, low turbulent mixing or gap filling of lost data by implementation of look-up tables. In Portugal an eddy covariance unit was implemented, supported by CARBOEUROFLUX in a eucalyptus plantation, intensively managed for pulp

industry. Eucalyptus forests of this kind are widely extended by an area of $700 \cdot 10^3$ hectares all over the country. The purpose of this paper is to make a presentation of the data of carbon dioxide atmospheric fluxes for the period of twenty two months, from February of 2002 to December of 2003 and water vapor atmospheric flux in the surface layer over the Espirra site. The main corrections, quality tests and gap filling strategy are provided, as well as an overview about the seasonality of energy and mass fluxes and the influence of climatological variables on them.

Site description and methods

In order to evaluate the carbon sequestration in a typical eucalyptus plantation, an eddy covariance unit was installed at a 32 meter tower, to measure turbulent fluxes of mass and energy. The experimental site was the 300 hectare eucalyptus plantation of "Herdade da Espirra", (38°38'N, 8°36'W) planted in a Dystric Cambisol type soil with a mean deepness of 1.3 m. The cover was located in a flat terrain, extending for distances from 700 m to 1800 m in the several directions. Considering the criterion of the abscissa corresponding to the point of maximum contribution for the flow (SHUEPP *et al.*, 1990), these lengths are considered to provide an adequate fetch.

The mean height canopy of 20 meters, spacing 3*3m, second coppice, 9 years aged and an estimated leaf area index of 3.1. The eddy covariance unit comprised one ultrasonic Gill anemometer R2, and one open path analyzer IRGA Li-7500. Measurements of CO₂ and H₂O fluxes in the constant flux layer were made continuously since February 2002. The data of instantaneous fluctuations of

three velocity components, air sonic temperature and carbon dioxide and water vapor concentrations, measured at a 20.8 Hz rate, were submitted to two axes coordinate rotation, calculation of eddy fluxes by fluctuations obtained by linear detrending of thirty minutes files, Webb-Leuning correction for density fluctuations and Schotanus correction for sonic temperature.

Micrometeorological data used for the elaboration look-up tables and for analysis of the influence of climate parameters in eddy fluxes, were recorded by a automatic weather station. Incident global solar radiation was measured with a piranometer Kipp & Zonen, model CM6B. Mean air temperature was measured with Cu-Cons. thermocouples of 0.15 mm diameter. The wind velocity and direction at the top of the tower were measured by cup anemometers "Vector Instruments", model A110R and wind vane of the same mark, model W200P. Electric power was provided by a unit of solar panels and batteries.

Data quality control of the eddy covariance unit was designed to control missing data, e.g. due to electric power failing, spikes representing high oscillation values, caused for instance by rain drops in the instruments and low turbulent conditions ($u_* < 0.2\text{m/s}$). A gap filling by look-up tables for eddy fluxes of carbon dioxide and water vapor was applied, according to the standard technique indicated in (FALGE *et al.*, 2001). Tables were created to represent the variation of CO₂ and water vapor fluxes with physical data, parameterized in a basis of 35 classes of air temperature and 23 classes of global solar incident radiation, evenly spanned in the ranges of respectively -5°C to 40°C (-5°C and

45°C in Summer) and 47.62 $\mu\text{molm}^{-2}\text{s}^{-1}$ to 5238.2 $\mu\text{molm}^{-2}\text{s}^{-1}$. Those look-up tables were used to obtain linearly interpolated (or extrapolated) data for fluxes of carbon dioxide and water vapor, missed or rejected by quality control proceedings, considering the recorded mean air temperature and global solar radiation of the corresponding thirty minute intervals. The total percentage of eddy fluxes of carbon dioxide and water vapor that were missing or rejected by quality control proceedings were 48.2%, divided in 39.9% for daytime and 56% for nighttime periods. Those percentages, are a bit high when ranked with means of fluxes for 18 sites (FALGE *et al.*, 2001), of 32.6% for total periods, 32.6% for daytime and 37% for nighttime. As about half of the non-qualified data were due to systematic missing records provoked by failures in electric system, there exists some room for future improvement in quality data performance, if some investment is made in that system. The circumstance that 11 of the 18 sites cited in FALGE *et al.*, 2001, have percentages of non-qualified data greater than 40%, with four of them superior to 48.2%, is, on the other hand, indicative that the data of Espirra site, here presented, are not deprived of the necessary quality to validate the results obtained. CARRARA *et al.*, 2003, also report results of 54% of missed or rejected total data for five years, in the CARBOEUROFLUX Brasschaat site of mixed forest in Belgium.

Results and discussion

Carbon fluxes

The monthly data of carbon flux are shown in Figure 1.

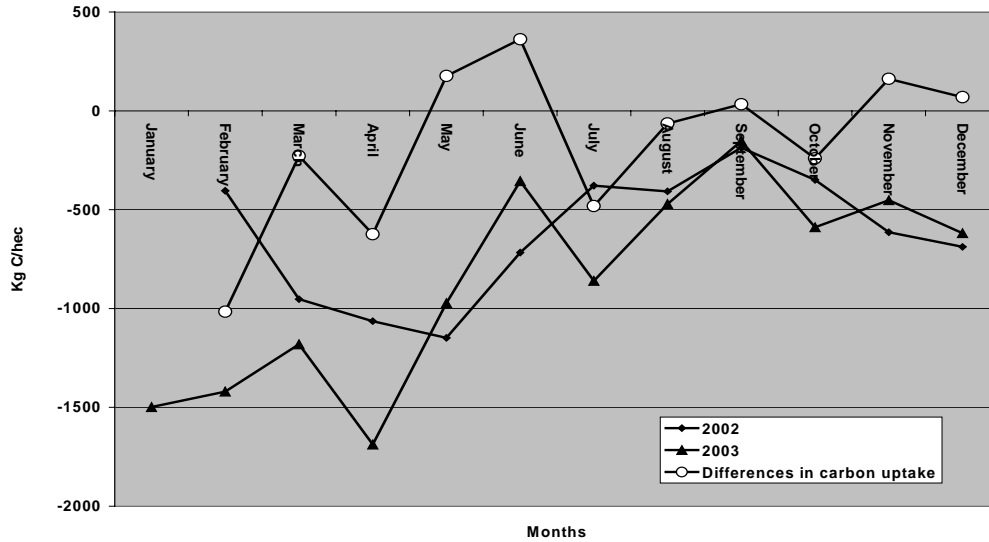


Figure 1 – Monthly carbon uptake, February 2002 to December 2003

The results show a significant seasonal pattern of atmospheric fluxes with the eucalyptus plantation behaving as a true carbon sink. The net ecosystem exchange is obtained by the following equation:

$$NEE = F_c + F_{\Delta S} + F_A$$

where $F_c = w'c'$ is the covariant flux of CO_2 , $F_{\Delta S}$ is the change in storage of CO_2 in the soil-air volume beneath the tower and F_A is the advection term.

According to SCHMID *et al.*, 2000, storage change is negligible for periods from a few days to years in the soil-air volume beneath the tower. Advection may be disregarded in conditions of sufficient fetch. So the data of measured fluxes were taken as representative of NEE. In monthly terms, averages of uptake at 2002 and 2003 were of 628 and 855 KgC/ha respectively. The average annual sink was of 8.9 tons

$Cha^{-1}yr^{-1}$ (890 $grCm^{-2} yr^{-1}$), values which are greater than uptakes 339-585 $grCm^{-2} yr^{-1}$ obtained for maritime-Mediterranean forests in EUROFLUX sites in the period of 1992-2000, (FALGE *et al.*, 2002) or to ranges of data of uptake of 6.7 $tonCha^{-1}yr^{-1}$ to releases of 0.9 $tonCha^{-1}yr^{-1}$ (VALENTINI *et al.*, 2000) for the period 1996-1998, collected in sites of 15 European forests. In the months from July to August of 2002 and 2003, with almost null precipitation (Figure 2), higher air temperatures (Figure 4) corresponding to monthly means of respectively 18.8 and 21.2°C, a smaller carbon uptaking, was a consequence of both to partial stomatal closure for minimizing water vapor losses and to increased soil respiration. An interplay between carbon and water vapor fluxes is thereby obvious.

Monthly air temperature was the main climatic parameter detected to

affect C uptaking (Figure 3). Monthly means of air temperature plotted in Figure 4, representing a variation between 9.5 and 23.7°C with mean 16.14±4.3°C. A sampling of two years is a bit small to permit a comparative analysis of annual variation, but the

mean air temperature increase in 2003 of 1.8°C in the period March-September, (Figure 4), was certainly contributive to soil temperature changes and thereby to ecosystem respiration and/or CO₂ uptake differences registered.

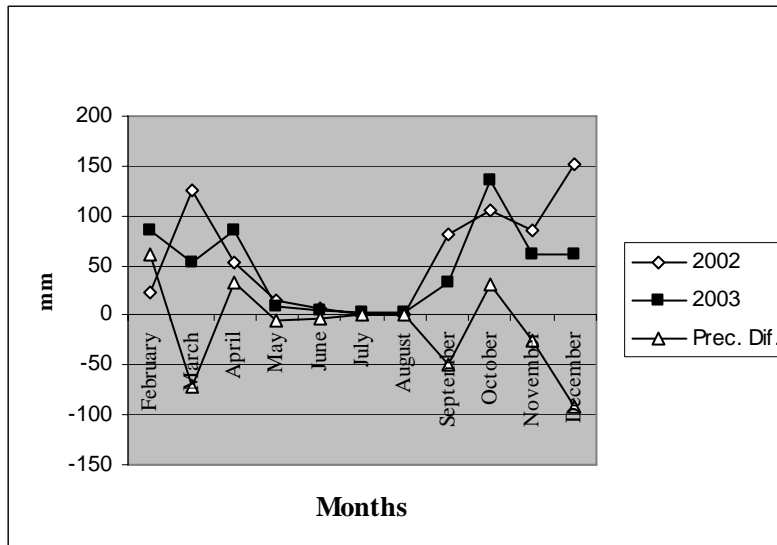


Figure 2 – Monthly precipitation from February 2002 to December 2003

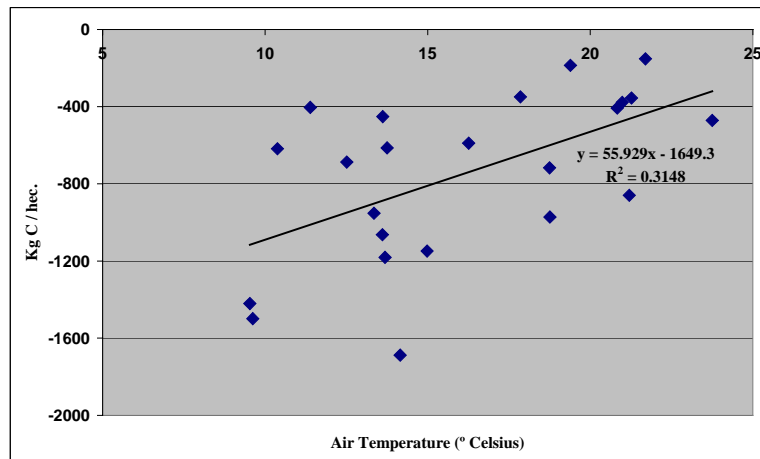


Figure 3 – Monthly variation of carbon uptake with mean air temperature

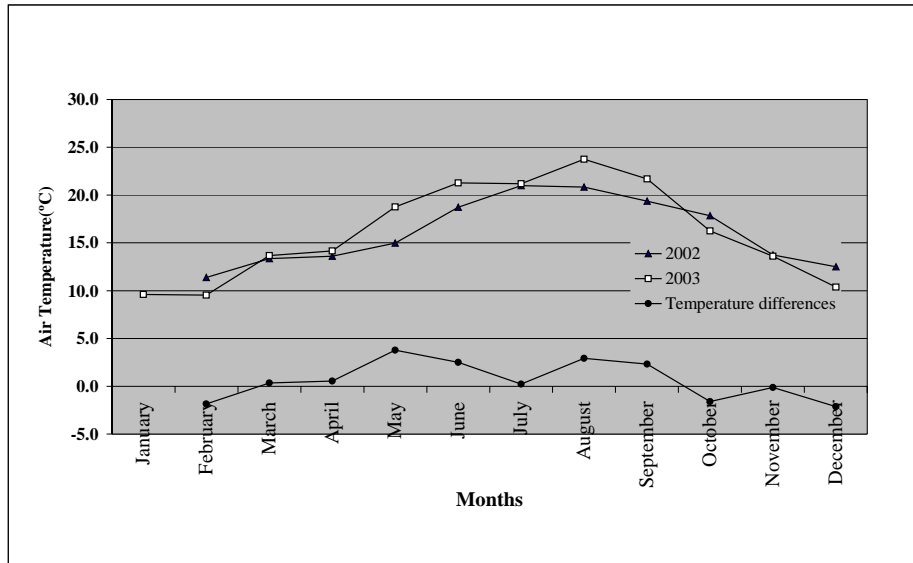


Figure 4 – Monthly average air temperatures from February 2002 to December 2003

The restraint in absorption in the two summers is a not a current event in CARBOEUROFLUX sites, notwithstanding the fact that uptake of carbon during the colder months is indicative of a Mediterranean forest year-long type assimilation (FALGE *et al.*, 2002). The annual pattern of more temperate and boreal sites shows a more confined season with a larger amplitude of carbon sequestration in summer. The daily trend of CO₂ uptake, shown in Figure 5, is dependent of air humidity and PAR radiation. The curves graphed are representative of the mean values of the hourly data of periods of two months. Those curves, representative of all seasons, are the typically u-shaped form, described in references as for instance KOWALSKI *et al.*, 2003 or SCHMID *et al.*, 2000. The non-parallel curves in Figure 5 are a result of the differences in seasonal stomatal partial closure and soil respiration, above mentioned. The summer and annual decreases in carbon uptake, are

typified by a variation in 2002 of the noon means of $-12.6 \mu\text{molCO}_2/\text{m}^2$ for the period May-June to $-5.0 \mu\text{molCO}_2/\text{m}^2$ for the period July-August (Figure 6).

In 2003 the equivalent noon decrease in uptake was observed from $-14 \mu\text{molCO}_2/\text{m}^2$ for March-April to $-9 \mu\text{molCO}_2/\text{m}^2$ for May-June.

The influence of global solar radiation, in carbon uptake is evident in the form of Figures 7 and 8. The data of the graphs, with different curve forms as a consequence of the soil respiration increment and of seasonal partial closure of stomatal pores, is correspondent to daily periods with visible radiation (7h a.m. to 7h30m p.m. in February-March 2002 and 5h30m a.m. to 8h p.m. in May-June 2002). The mean hourly values of global solar radiation in the periods considered, varied from a minimum of near $8\text{W}/\text{m}^2$ at 7h a.m. to maximums of 619 and $802\text{W}/\text{m}^2$ at 1h30m p.m. of respectively February-March and May-June 2002.

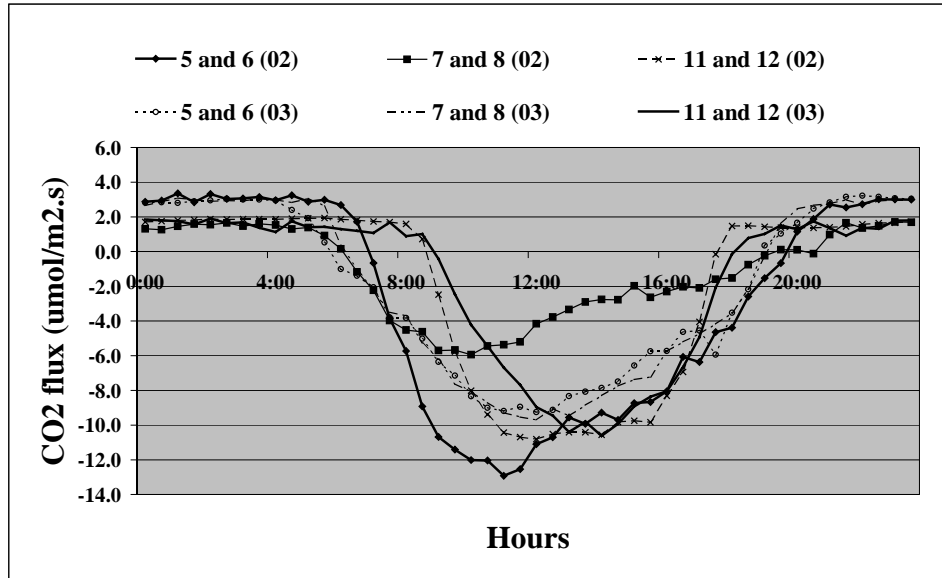


Figure 5 – Average daily pattern of CO₂ flux by bimensal periods

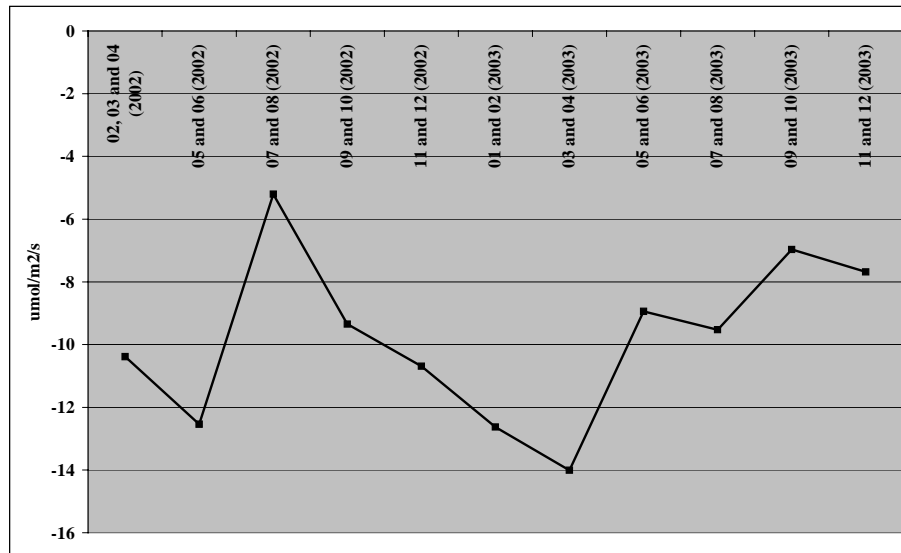


Figure 6 – Daily carbon uptake means at noon during bimensal periods

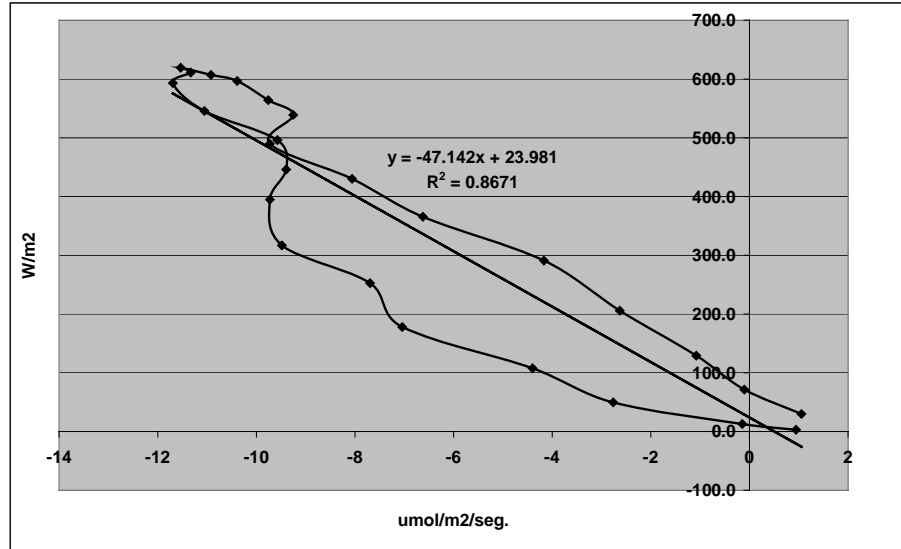


Figure 7 – Carbon uptake vs. global solar radiation in February and March 2002

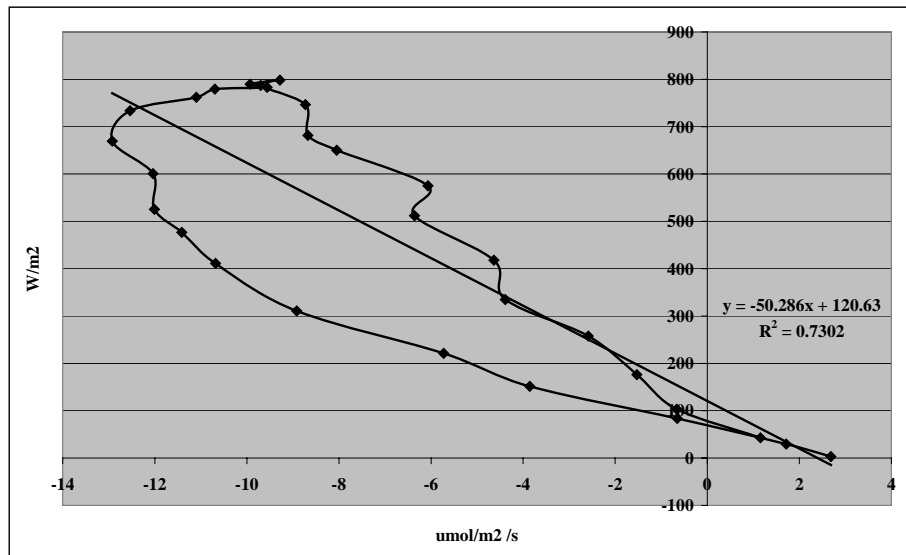


Figure 8 – Carbon uptake vs. global solar radiation in May and June 2002

Evapotranspiration

The monthly mean evapotranspiration rate in the period February 2002 - December 2003 was of about 556.2ton/ha, comparing against 556.5ton/ha of water precipitated in the same period. The monthly evolution of water vapor flow is graphed in Figure 9, showing a monthly mean increment of 431ton/ha simultaneous with a increase of 2.4°C in air temperature in the period of May-August 2003, relatively to the same months of 2002. It may be noticed that in both years there exists two decreases of evapotranspiration, one more steep in summer (May (2002)-June (2003) to August (2002)-September (2003)), leading to the smallest values of evapotranspiration in the whole year,

and one more gentle in winter from November to January. Again, this is not the common pattern of more temperate places (KOWALSKI *et al.*, 2003, SCHMID *et al.*, 2000), with the restrictions of pore openings in summer being the main specific characteristic of this kind of site. The increased loss of water vapor to atmosphere in May-August of 2003, compared to 2002, may be attributed to soil evapotranspiration. The decreases of evapotranspiration in winter are typical of that season in agreement with other sites (SCHMID *et al.*, 2000, KOWALSKI *et al.*, 2003). Data of latent heat adimensionalized to global solar radiation (Figure 10), show, for the same reasons, a similar tendency of reduction of latent heat in summer.

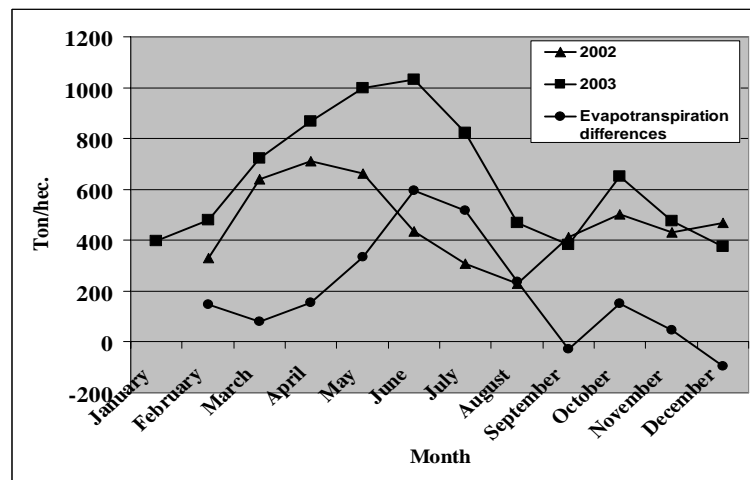


Figure 9 – Monthly evapotranspiration from February 2002 to December 2003

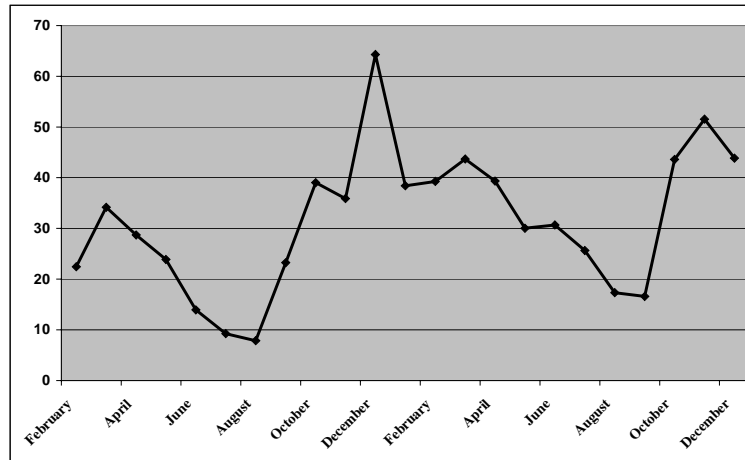


Figure 10 - Fraction of latent heat to global solar radiation from February 2002 do December 2003

Conclusions

The atmospheric carbon flux by eddy covariance for evaluation of NEE during 22 months, in the period from February 2002 to December 2003, showed that the eucalyptus forest was a strong carbon sink of $8.9 \text{ tonsCha}^{-1} \text{ yr}^{-1}$ ($890 \text{ g m}^{-2} \text{ yr}^{-1}$). The CO_2 uptake followed a Mediterranean forest year-long assimilation with a notorious restriction in summer due to stomatal closure. Monthly evapotranspiration in the site was of about 556.2 ton/ha. , comparing against 556.54 ton/ha of precipitation. Monthly air temperature and hourly global solar radiation were two main parameters influencing carbon uptake. For future measurements, some room for improvement of data quality is available by minimizing systematic recording losses due to power failures.

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