Net CO_2 exchange in a rural area of the upper Spanish plateau

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ABSTRACT:
In 2004 we installed a CO_2 eddy-correlation system at the CIBA centre located in an agriculture area in the geographical centre of the semi-arid upper Spanish plateau. 30-min Net Ecosystem Exchange measurements, NEE, were systematically performed from February to January 2005 (except in August). The period of study was dominated by drought, the yearly accumulated rainfall amounting to 300 mm. This paper presents the most relevant experimental results obtained, identifies the main driving factors governing NEE and assesses the influence of one of the most common vegetation indexes, the Normalized Difference Vegetation Index, NDVI, on gross primary production (GPP) in the growing season. The NDVI data used correspond to the MODIS 16-day composites. The results obtained show: 1) a marked seasonal variation featured by CO_2 uptake during the growing season (March-June 16) and CO_2 emissions from October to January. 2) low monthly NEE means ranging from 0.21 to -1.39 $\mu mol/m^2.s$, 3) consistent diurnal cycles with their corresponding Photosynthetic Active Radiation, PAR, and vegetation cover evolution and 4) a satisfactory linear relationship of GPP versus MODIS 16-day NDVI during the growing season (R^2=81.8%).

Key words: CO_2 exchange, Net Ecosystem Exchange, NEE, Eddy, Gross primary production, GPP, Relationship between GPP and NDVI.

Intercambio Neto de CO_2 en un Área Rural Española de la Meseta Norte

RESUMEN:
En 2004 instalamos un sistema de medida de flujos turbulentos de CO_2 *(eddy-correlation)* en el CIBA, situado en un área agrícola semiárida de la meseta norte española. Durante períodos de 30 min. se calcularon sistemáticamente los flujos netos, NEE, desde febrero de 2004 hasta enero de 2005 (excepto en agosto). El período de estudio estuvo dominado por la sequía siendo la precipitación acumulada de 300 mm. Este trabajo presenta los resultados experimentales más relevantes, identifica los principales factores que gobiernan la variabilidad de NEE y valora la influencia de uno de los índices de vegetación más característicos, NDVI, sobre la producción primaria neta, GPP durante el período de crecimiento vegetativo. Los datos de NDVI utilizados fueron los compuestos MODIs de 16 días. Los resultados obtenidos muestran: 1) una marcada variación estacional caracterizada por absorción fotosintética durante el período de crecimiento vegetativo (marzo-junio 16), y emisiones de CO_2 desde octubre hasta enero; 2) bajos valores de NEE, comprendidos entre 0,21 y -1,39 $\mu mol/m^2.s$; 3) ciclos diarios consistentes con los correspondientes de la radiación fotosintética activa, PAR, y la evolución de la cubierta vegetal; y 4) una satisfactoria correlación lineal de GPP con los compuestos de NDVI de 16-días durante el período de crecimiento vegetativo (R^2=81,8%).

Palabras clave: flujos de CO_2, intercambio neto de CO_2, NEE, turbulencia, producción primaria neta, GPP, relación entre GPP y NDVI.

1. INTRODUCTION

Over the last one hundred years atmospheric CO_2 concentrations have increased by over 28%, the longer temporal series recorded in Manua Loa (**http://www.cmdl.noaa.gov**) showing a continuous increasing trend. Similar results have been obtained in other rural areas, with annual trends above 2.3 ppm/year being reported. In Castile and Leon, measurements performed since 2000 have shown a higher trend, around 3 ppm/year (Sánchez et al. 2005).

At present there is general consensus regarding the influence of greenhouse gases on climate change. Over the last century surface temperature has risen by approximately 0.76 ºC at a global scale and there is also abundant evidence that spring is arriving increasingly earlier whilst autumn is being delayed. Further evidence is the presence of anomalies in the geographic rainfall distribution in the Northern hemisphere (IPCC, 2007). Increase in temperature and/or decline in rainfall can strongly influence the content of soil moisture leading, among other effects, to an increase in both the number and severity of droughts, especially in Southern Europe. All of these factors can dramatically impact available vegetation energy and its partitioning in latent and sensible heat fluxes. Finally, a rise in temperature and a drop in moisture can directly affect stomata opening control (Meyers, 2001), a key factor governing CO_2 uptake. Although according to the recent recommendations of the IPCC, emission abatement strategies should be urgently adopted to stabilise or reduce CO_2 trends, accurate quantification of CO_2 permanence in the atmosphere also requires quantification of its major sinks, namely oceans and vegetation cover. Yet, although knowledge of the carbon cycle has significantly improved in recent decades, uncertainties still remain (Adams and Piovesan, 2002).

An assessment of NEE historical series recorded over relatively long time periods in the CARBOEUROFLUX and FLUXNET networks has evidenced the unequal ability of CO_2 uptake in different ecosystems (Keeling et al. 1996; Running et al. 1999). NEE obtained have exhibited significant geographical variability, ranging from values close to 700 g C/m^2.year and zero. To further complicate matters, the behaviour of the same biomes at similar latitudes in the USA and EU differs significantly, a fact which might be attributed, among other factors, to the thermal differences observed in the two continents (Baldocchi et al. 2001).

NEE fluxes are typically measured using fast response instrumentation by means of the eddy-correlation technique (Baldocchi and Meyers, 1998). This procedure is considered one of the most powerful tools to study the carbon cycle since it provides net fluxes, differences between CO_2 uptake and soil efflux. Moreover, the instrumentation is based on the IRGA technique (http://www.licor.com/) and simultaneously provides water vapour fluxes, which play an important role in vegetation growth and consequently in CO_2 uptake. Since this procedure provides dynamic information on NEE, it has been widely used around the world and is in fact considered the benchmark method to validate or intercompare results directly obtained by remote sensing (Leuning et al. 2005). The significant increase in the number of satellite sensors orbiting the Earth which are able to supply information on vegetation cover evolution offers a promising future to parameterise "in situ" observations as a function of the data provided by remote sensing.

With the aim of increasing current knowledge of the carbon cycle, we performed systematic NEE measurements using the eddy-correlation technique at CIBA in 2004. The goal of this paper is to present the most salient experimental results obtained, describe the major driving factors controlling NEE and assess the possibilities of remote sensing to quantify the temporal evolution of carbon sinks. To accomplish the last objective we used MODIS NDVI 16-day composites as a key parameter.

2. DESCRIPTION OF THE SITE. MATERIAL AND METHODS

NEE measurements were performed at the CIBA centre located in the geographical centre of the semi-arid upper Spanish plateau. The dominant land use in the surrounding area corresponds to non-irrigated wheat. However, the great inter-annual variability in the crop types in some of the surrounding plots should be mentioned. This is particularly true in one extensive plot adjacent to CIBA in which crop rotation, e.g., fallow, beans and wheat, has been a common feature in recent years. Specifically in 2004, the period of study dealt with in this paper, this plot remained fallow the whole year.

CO_2 net fluxes were measured by means of the eddy correlation technique using a Li-6262 system and a sonic Campbell CSAT3. The system operated at 10 Hz and was installed at the top of a 10 m high mast. The instantaneous data were stored on a PC and afterwards processed each 30 min using a procedure similar to that described by Rodriguez (1998). Each temporal series was linearly detrended and filtered to remove the nonstationarities associated to lower frequencies. According to the experimental data at CIBA the cut off frequency was 0.008 Hz. The Webb correction, often used in the literature, has not been applied due to its low contribution (less than 3%) especially during the period of maximum interest (March-June 16, see below). NEE were determined by adding the concurrent CO_2 storage values to the CO_2 net fluxes. The storage term was calculated following standard methods (e.g., Pilegaard et al. 2001). In this paper, typical sign convention has been used: negative and positive fluxes mean uptake and emissions, respectively. In order to ensure quality of the 30-min data, outliers above or below 3.0 or 1.5 times the interquartile range, depending on the statistical distribution of each 30-min data, were removed from the calculations. Most of the data rejected corresponded to weak mechanic turbulence recorded especially at night, friction velocity u* below 0.1 m/s, a lower restrictive threshold than some of the data rejection criterion documented in the literature, e.g, u*>0.2-0.25 m/s (Leuning et al. 2005). Measurements were performed from February 2004 to January 2005, and were only interrupted in August. The mast was equipped with other slow response probes, such as a quantum sensor to measure PAR and another for global solar radiation, SR. Both were installed 2 m above ground level. These data were stored on a DASIBI 8001 datalogger and also processed as mean 30-min values. Other common meteorological variables, such as wind speed, wind direction, soil temperature and soil moisture were taken from the 100 m mast measurements routinely performed at CIBA. Finally, the MODIS 16-day NDVI composites were directly collected from the NASA web-site. Calculations of NDVI may be found, for instance, in van Leeuwen (van Leeuwen et al. 1994).

3. RESULTS

The period of study, 2004, was dominated by drought. Annual accumulated rainfall was 300 mm, a value considerably lower than the climatological value in Valladolid, around 450 mm, (Junta de Castilla y León, 1995). Drought was a common feature during most of the months, proving particularly severe from January to May, during which the accumulated rainfall declined approximately to 50% of the climatological values. Extreme temperatures ranged from 30.5 to -6.9 ºC, and maximum PAR values were close to 2000 µmol/m^2.s, a value fully consistent with the high solar radiation prevailing in Spain. Taking into account the aridity of the Spanish plateau, as might be expected, high nocturnal temperature inversions (calculated as the differences between the values recorded at 100 and 6 m), were extremely frequent during most months, maximum values being 7.0 ºC. During daytime temperature gradients were lower, the highest value being -2.7 ºC. The lower diurnal value reveals the strong convection activity at the measuring site.

3.1. SEASONAL AND DIURNAL VARIATION

The monthly means, depicted in Fig. 1, showed a seasonal variation consistent with the crop growing period. CO_2 uptake was first noticed in March, increased in April, peaked in May and dramatically declined throughout June coinciding with the onset of vegetation senescence. From October to January the site behaved as a weak carbon source. Monthly mean values recorded were generally low - ranging from -1.39 µmol/m^2.s in May to 0.21 µmol/m^2.s in November - compared with other results on wheat reported in the literature (Wang et al. 2006). The low fluxes, even in May, might be attributed to the drought conditions prevailing in 2004 and likely to failure of the fallow as a CO_2 sink in the plot adjacent to CIBA. During the whole year the overall mean value was -0.36 µmol/m^2.s, revealing the dominance of CO_2 uptake against respiration.

In the growing season, CO_2 uptake showed great hourly and daily variability. Figs. 2 a-d depict the monthly ensemble averaged 30-min values recorded from March to June. Vertical bars represent the Least Significant Difference intervals (LSD) with a 95% confidence level.

As may be inferred from these Figures, the ecosystem systematically released and gained CO_2 during nighttime and daytime, respectively, indicating the dominance of respiration and photosynthetic uptake during each period of time.

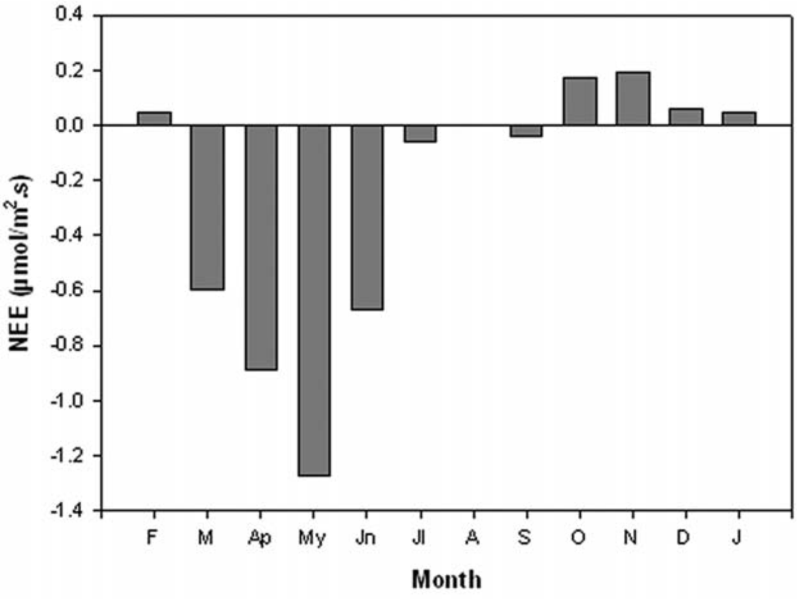
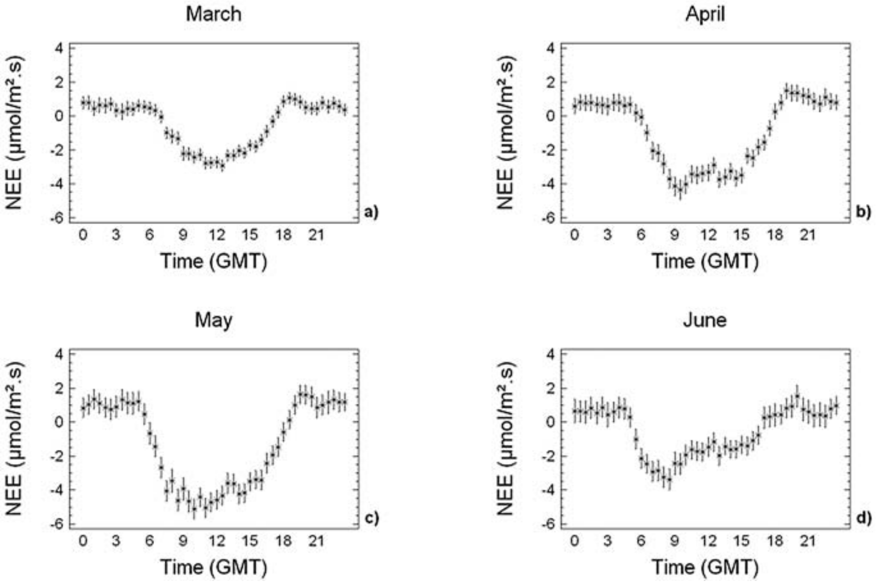


Figure 1.- NEE seasonal variation during 2004 at CIBA.

The increasing amplitude from March to May together with the wider period of time featured by CO_2 uptake were in agreement with their corresponding diurnal PAR patterns (not shown in this paper), revealing the strong influence of this parameter on NEE fluxes as will be discussed in detail later. The lower amplitude in June together with the anticipation of maximum CO_2 uptake towards the early morning might be attributed to the increased water stress occurring on the progressive seasonal rise in air temperature and the onset of vegetation senescence observed throughout first week of June. Despite the similarities in the CO_2 and PAR diurnal cycles, some interesting differences should be mentioned. The first corresponds to the lack of temporal simultaneity between CO_2 uptake and PAR at sunrise and sunset, respectively. CO_2 uptake began to be effective with a 1-2 h delay with regard to PAR, and again released CO_2 1-2 h before sunset. This result, particularly evident in April and May, and also documented in forests, proves that photosynthetic activity is too weak to offset respiration when solar radiation is weak. The second point refers to some features of the shape of the diurnal cycle. Also worthy of note is the rapid increase and decline of CO_2 uptake recorded in the early morning, at around 7-8 h and late-afternoon, 17-19 h, respectively. These results could be attributed to the superimposed effects of the environmental conditions involved in canopy photosynthetic uptake, namely, optimal temperature and moisture, and the enhancement of upward/downward fluxes at the beginning of soil heating/cooling.

Another interesting aspect to be mentioned is the low respiration values, RE, obtained as compared with those recorded over barley using chambers (Sánchez et



Figures 2 a-d.- NEE diurnal cycles during the growing season at CIBA: a) March, b) April, c) May and d) June.

al. 2003). A plausible reason for the significant lower RE observed could be attributed to the frequent weak winds and calm conditions as well as the very stably stratified atmospheric conditions at CIBA, as has already been documented in the literature (Goulden et al. 1996; Law et al. 1999). This effect, superimposed on the presence of drought and the expected large contribution of the fallow plot, appear to be the most likely explanation to justify the low fluxes obtained during nighttime.

3.2. INFLUENCE OF PAR ON NEE

NEE are expected to be dependent on the driving factors controlling stomata opening, such as PAR, air temperature, moisture as well as parameters describing the vegetation cover, such as, LAI or NDVI (Wiley et al. 2007). Of all these parameters, PAR is considered one of the major factors regulating NEE, and has in fact frequently been used in practical applications to parameterise fluxes by means of the well-known Michaelis-Menten empirical model (Hollinger et al. 1998; Pilegaard et al. 2001):

$$NEE = RE + P_{max}.\ PAR\,/\,(PAR + K_{50})$$

Here P_{max} and K_{50} represent the potential maximum photosynthetic capacity and the Michaelis-Menten constant, respectively. K_{50} is the PAR value at which NEE reach 50% of the maximum value and it is defined as - P_{max}/α , where α is an indicator of the initial light use efficiency of the canopy. In order to assess the temporal evolution of the parameter estimates this equation has been fitted to each monthly data of the growing season (March-June). Due to some operational problems of the quantum sensor, the missing PAR data were filled in by considering the results of the linear fit between PAR and SR data (R^2= 99.6%), yielding roughly, PAR (µmol/m^2.s)=2·SR (W/m^2) .

The parameter estimates are shown in Table I. The monthly non-linear fits obtained during the growing season (see second column) yielded satisfactory R^2 values, 55.8, 70.0 and 70.9%, in March, April and May, respectively. June saw a dramatic drop to 32.9% evidencing the vegetation's weaker ability to capture carbon during the senescence period. P_{max} exhibited a gradual increase from March to May, -6.02, -7.15 and - 9.68 µmol/m^2.s, respectively, dropping to -3.74 µmol/m^2.s in June. This was the month characterised by the highest contrasted NEE records. The greatest values corresponded to those recorded during the first days after intensive rainfall, 28 mm in a single day, which occurred at the end of May. This severe event yielded a marked increase in NEE (in fact the values were substantially higher than those recorded during the last week of May). From June 1st, NEE fluxes began to decline progressively and roughly eight days later, in the absence of rainfall, remained very low with a similar order of magnitude to July. K_{50} approximated to half of the maximum PAR from March to May, 1109, 733, 885 µmol/m^2.s. The decline in June, 565 µmol/m^2.s, is in agreement with the main features of the diurnal NEE cycle described earlier. Finally, as expected, RE and α followed a similar trend to the cover vegetation evolution. The RE values evolved from 0.45 to 1.16 µmol/m^2.s, dropping to 0.80 µmol/m^2.s in June and α rose from 0.0054 to 0.0109 µmol/µmol during the same months, again declining in June to 0.0066 µmol/ µmol.

Table I.- Parameter estimates of the Michaelis-Menten model fitted to the 30-min NEE fluxes for each one of the months during the growing period.

Month	**R^2**	**P_{max}** *(µmol/m^2.s)*	**K_{50}** *(µmol/m^2.s)*	**α** *(µmol/µmol)*	**RE** *(µmol/m^2.s)*
March	55.8	-6.02	1109	0.0054	0.45
April	70.0	-7.15	733	0.0097	0.91
May	70.9	-9.68	885	0.0109	1.16
June	32.9	-3.74	565	0.0066	0.80

3.3. INFLUENCE OF NDVI ON GPP

Of particular interest in the carbon cycle description is GPP, the difference between NEE and respiration RE, as it directly accounts for the CO_2 assimilated by plants or the carbon sequestration ability of a specific biome. In this paper GPP

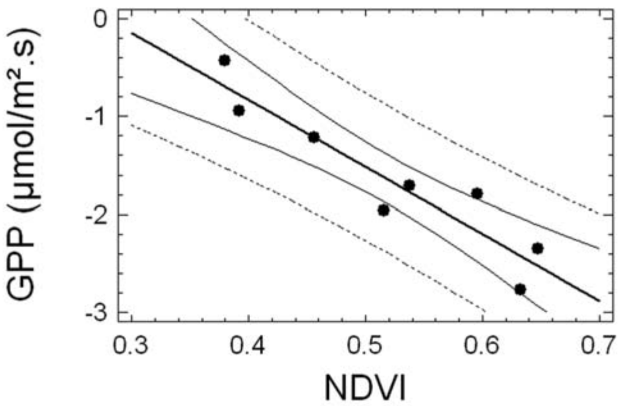


Figure 3.- Influence of NDVI 16-day composites on GPP during the growing season at CIBA (March-June 16). Dots correspond to the observational data. The bold line indicates the best fit and the full and dotted thick external lines the 95 intervals for confidence and prediction.

were determined as follows: 1) By considering the overall NEE 30-min data (diurnal and nocturnal), the means concurrent with its corresponding MODIS 16-day NDVI composite was determined. 2) The respiration term, RE, was calculated in a similar manner but only selecting the nocturnal data, the time of day when only respiration takes place. 3) The values obtained in the two previous steps were subtracted and a relationship between GPP versus NDVI was then performed. The satisfactory linear fit during the growing season (from March 1st to June 15th), as can be directly inferred by examining Fig. 3, (R^2=81.8%), reveals the important role of remote sensing to quantify the temporal evolution of carbon sinks at the measuring site.

4. CONCLUSIONS

NEE at CIBA exhibited a seasonal variation featured by CO_2 uptake during the growing season, from March to June 16, whereas the ecosystem behaved as a carbon source from October to January. The low NEE obtained might be attributed to the superimposed effects of the drought that affected central Spain in 2004 and the expected contribution of an extensive fallow plot adjacent to CIBA. In the growing season the ecosystem released CO_2 during nighttime and gained CO_2 during daytime. CO_2 uptake began to increase in March, peaked in May and significantly declined in June as a result of vegetation senescence. The variance of the non-linear fits using the Michaelis-Menten model for each growing month ranged from 55.8% to 70.9% in March and May, respectively, revealing the strong influence of PAR as a driving factor controlling the 30-min NEE fluxes. In June the influence of PAR dramatically dropped, the variance of the fit being 32.9%. Despite the limited data available in this study, the strong correlation between 16-day NDVI and GPP found in the growing season, R^2=81.8%, allows us to conclude the promising possibilities of remote sensing to quantify the temporal evolution of carbon sinks in the measuring site. However, to obtain definite conclusions additional measurements covering wider climatological situations than those prevailing in 2004 are necessary.

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