

Seasonal net carbon dioxide exchange of a beech forest with the atmosphere

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Abstract

The seasonal carbon dioxide exchange of a beech forest of Central Italy was studied by means of the eddy covariance technique. Additional measurements of biomass respiration with cuvettes and relationship of carbon dioxide exchanges with temperature and light were used to interpolate missing data during the dormant and part of the growing season.

The net ecosystem production of the forest equals $472 \text{ g C m}^{-2} \text{ y}^{-1}$ while the gross ecosystem production $1016 \text{ g C m}^{-2} \text{ y}^{-1}$ and respiration $544 \text{ g C m}^{-2} \text{ y}^{-1}$. These estimates are compared with the net primary production determined by direct biomass sampling which amounts to $802 \text{ g C m}^{-2} \text{ y}^{-1}$.

Keywords: carbon balance, *fagus sylvatica* L., eddy covariance, primary production

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Introduction

Terrestrial ecosystems contribute to the 64% of the total planetary net primary production and forests, in particular, to the 42% (Whittaker & Likens 1975). In this respect forests play an important role in the global carbon cycle, as suggested by recent papers (Tans *et al.* 1990; Enting & Mansbridge 1991; Sundquist 1993; Schimel 1995), as they contain a relatively large and stable storage pool of atmospheric carbon.

The carbon sequestering potential of planted (Vitousek 1991) and natural forests has been recently discussed but its quantitative estimation is still under debate. For several countries, such as UK (Jarvis 1994), the annual sequestration of carbon by forests has increased in the last 20 years; on the other hand, several studies have shown a decrease of the biospheric sink, since 1976, due to the increase of forest depletion on a global scale (Auclair & Bedford 1993).

Quantitative estimation of the carbon sequestration at ecosystem level has been approached in the past by means of destructive sampling (Lieth & Whittaker 1975) or more recently by remote sensing (Fung *et al.* 1987).

It is only recently, by means of the eddy covariance technique (Baldocchi *et al.* 1988), that it has been possible to determine the net carbon exchanges of vegetation communities on a long-term basis (Wofsy *et al.* 1993). The use of eddy covariance to assess the total carbon exchange

rate at the ecosystem level has several advantages: it is not destructive and labour-consuming; it can be operated on a scale from hours to years; it is possible to derive functional relationships between carbon exchanges and environmental factors; and it takes into account all the biomass components including those usually difficult to sample (roots, leaves, twigs, etc.).

However, several errors and uncertainties are associated with the technique (see Goulden *et al.* and Moncrieff *et al.* 1996, this issue, pp. 169 and 231 ff.).

In this paper the eddy covariance technique is employed to investigate the seasonal carbon dioxide flux of a temperate forest, and a comparison with a traditional carbon balance assessment is presented.

Materials and methods

The study forest is situated in Central Italy near the village of Collesongo ($41^{\circ} 52' \text{ N}$, $13^{\circ} 38' \text{ E}$) at an elevation of 1564 m a.s.l. It is an almost pure high stand of *Fagus sylvatica* L. trees with a mean height of 20.2 m, a mean basal area of $26.4 \text{ m}^2 \text{ ha}^{-1}$ and a wood biomass of $294 \text{ m}^3 \text{ ha}^{-1}$. The principal features of the site, including climate and soil are shown in Table 1.

Eddy fluxes of sensible heat, water vapour and carbon dioxide have been determined by the eddy covariance technique (Baldocchi *et al.* 1988). The flux of a given scalar c (like CO_2) is given by:

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Table 1 Main climatic and vegetation features of the site

Species	<i>Fagus sylvatica</i> L.
Mean diameter	28.8 cm
Mean height	20.2 m
Basal area	26.4 m ² ha ⁻¹
Wood volume	294 m ³ ha ⁻¹
Wood increment	7 m ³ ha ⁻¹
Tree density	406 trees ha ⁻¹
Mean age	90 y
Mean air temperature	7.2 °C
Maximum air temperature	33.3 °C
Minimum air temperature	-24.1 °C
Mean precipitation	1100 mm
Soil type	calcareous
pH	5

$$F_c = \rho \overline{w'c'}, \quad (1)$$

where w' and c' are the vertical wind speed and scalar concentration fluctuations around the mean, respectively, and ρ is the density of dry air.

Several corrections are needed in (1) in order to take into account changes in air density due to simultaneous fluxes of water vapour and sensible heat. This problem has been discussed extensively by Webb *et al.* (1980), Leuning & Moncrieff (1990), Suyker & Verma (1993), from which correction equations have been derived.

The instrumental set-up consisted of a 3D sonic anemometer (Gill, UK) and a LI-6262 CO₂ and H₂O infra-red gas analyser (Licor, USA). A pump at the bottom of the line withdraws air through the analyser at a flow rate of about 6 L min⁻¹. Due to the high flow rate, the pressure inside the cell of the analyser was about 16 kPa below atmospheric and concentration was automatically corrected using a pressure transducer at the inlet of the LI6262.

During the season calibration was carried out every 15 days with reference gases. Changes of no more than 5–8% of the analyser gain were observed. A relative humidity sensor connected to the system software prevented the operation of the pump during rain or in humidity conditions exceeding condensation.

The eddy covariance instrumentation was installed on a mast, 5 m above the canopy, that was placed over the top of a scaffold. Power supply was given by solar panels plus a generator charging batteries for about three hours every day.

The observation period extended from 9 May 1993 to 3 November 1993 on a 24 h basis, with data collected every 30 min.

In order to check the overall system reliability for flux measurements two type of tests were performed: the spectral analysis of the turbulence signal and the energy balance closure.

Spectral analysis showed a cut-off frequency of the closed-path analyser at f (normalized frequency) ≈ 1 and a deviation from the sensible heat co-spectra of the order of 15% over a range of stability conditions. Corrections due to tube attenuation have been applied following Suyker *et al.* (1993) in order to take these problems into account.

The energy balance closure was achieved for the most of the measuring period with an error of $\pm 15\%$, with the largest deviations at the beginning and end of the day when net radiation was low.

Wood biomass and increment were calculated by forest mensuration at d.b.h. and core sampling. Wood volume was calculated by standard forest mensuration techniques, using harvested model trees to determine the stem shape coefficients.

Leaf area index was measured with the LAI2000 canopy analyser (Licor, Nebraska, USA) and leaf litter was collected in 28 sampling nests, periodically emptied (15 days) to avoid decomposition. Leaf area was determined in the lab after drying.

Soil cores (12 samples each sampling date) were collected to analyse the distribution of fine roots and their turnover. Soil core sampling was carried out 5 times (0–45 cm of depth) and 7 times (0–15 cm of depth). Calculation of fine root turnover was carried out following Van Praag *et al.* (1988).

The respiratory losses during the dormant season were estimated by measurements of stem and branch respiration by means of cuvettes and an IRGA analyser (ADC Inc., UK). Respiration fluxes were measured 7 times during the year on 4 trees of different d.b.h. (13, 18, 32, 37 cm). Furthermore stem respiration for 30 trees with d.b.h. ranging from 5 to 48 cm was measured during a specific campaign.

Results and discussion

In Fig. 1a the typical daily trend of carbon dioxide exchange of the forest with the atmosphere is presented. The negative sign of the CO₂ flux density (F_c) represents uptake from the vegetation while the positive sign represents a net release of CO₂ to the atmosphere. The graph represents 2 June 1993 when the forest had good water conditions of about 23% of soil moisture (by weight) at 30 cm of depth and -0.5 MPa of predawn water potential.

The CO₂ flux density peaks at about 12.00 hours ($-25 \mu\text{mol m}^{-2} \text{s}^{-1}$) in parallel with the photosynthetic photon flux density (PPFD). The net CO₂ exchange starts to be negative (vegetation uptake) at about 06.00 hours and becomes positive at about 19.00 hours.

A rapid decrease of F_c can be noted in the afternoon that can be explained either by a limitation of photosyn-

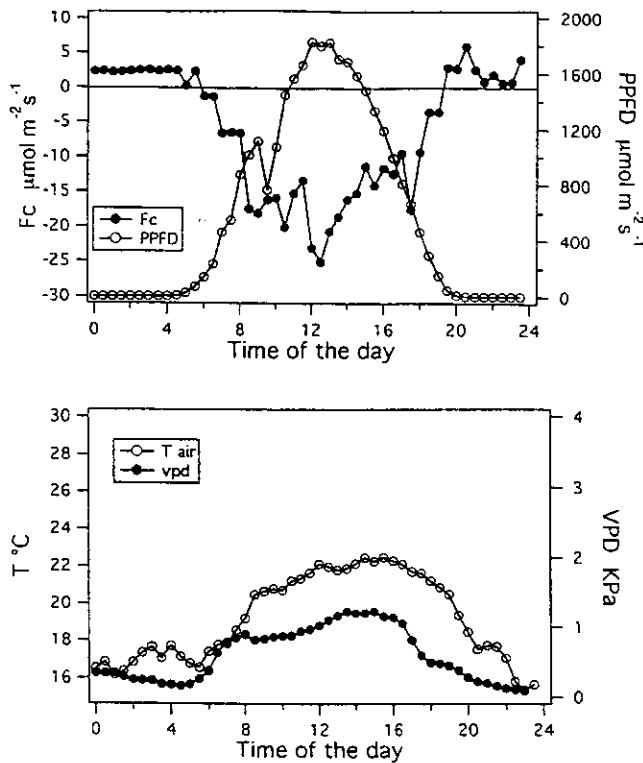


Fig. 1 (a) Daily trend of net carbon exchanges (F_c) and photosynthetic photon flux density (PPFD) for 2 June 1993 (b) Daily trend of air temperature and VPD for the same day.

thesis, due to a stomatal closure, or by an increase of the respiratory losses due to the higher temperatures. Actually the latter explanation seems to be more reasonable since VPD reaches a maximum of about 1 KPa, which is not particularly high, while the peak of air temperature occurs between 15.00 and 16.00 hours (see Fig. 1b).

A contrasting day is presented in Fig. 2a. The graph shows the daily trend on 3 August 1993. In this period the forest was short of water, as indicated by a soil moisture of 13% by weight at 30 cm of depth and a predawn water potential of -2.5 MPa. Temperature and VPD reached a maximum of 29.6 $^{\circ}\text{C}$ and 3.2 KPa, respectively.

The maximum F_c is depressed to about $-16 \mu\text{mol m}^{-2} \text{s}^{-1}$, indicating the effect of the reduced water availability. Furthermore the diurnal trend shifted to the morning hours, with the F_c peak at about 10.00 hours, a more rapid decrease of the afternoon values (starting from 13.00 hours) and a change of F_c sign at about 18.00 hours, earlier than the June trend.

These observations confirm the effect of water stress on the forest and the eddy flux clearly reveals an integrated response at the ecosystem level. Furthermore it is interesting to note that even if the site is located at about 1500 m a.s.l. and the beech forest is a typical vegetation type of

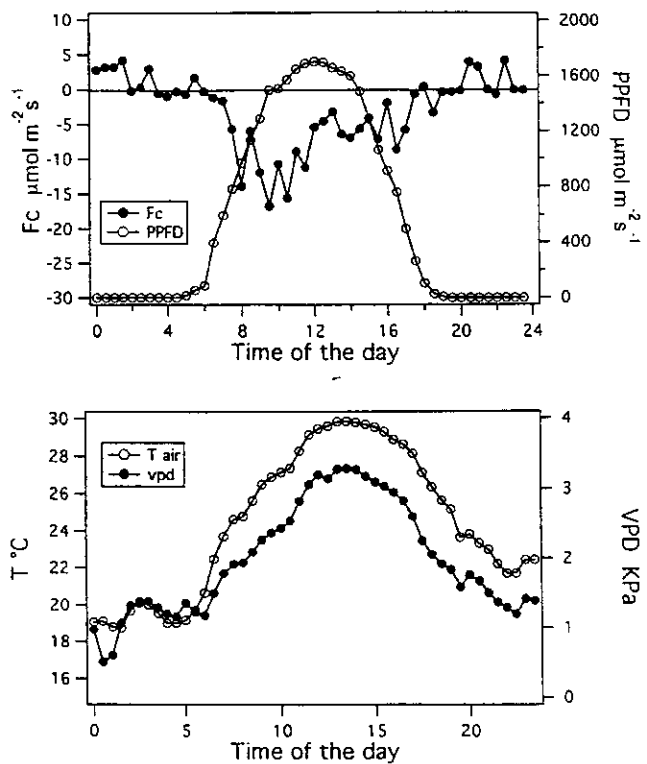


Fig. 2 (a) Daily trend of net carbon exchanges (F_c) and photosynthetic photon flux density (PPFD) for 3 August 1993 (b) Daily trend of air temperature and VPD for the same day.

continental sub-alpine climates, these forests in Central Southern Italy can experience periods of water stress that can have a significant impact on the carbon balance.

The main objective of the present work was to calculate an annual carbon balance of the forest, measuring eddy fluxes of carbon dioxide on a 24-h basis throughout the year. Many experiments today present successful results using similar techniques (Oechel *et al.* 1993; Wofsy *et al.* 1993; Greco & Baldocchi, 1996, this issue, p. 183). However, missing data, due to power supply failures, sensor calibration and maintenance, etc., are inevitable, as evidenced in this study. In our case we also had missing data due to the control on water condensation and to the long snow-cover period which made it impossible for us to record continuously during winter.

To remedy these problems we needed to interpolate missing data both for the vegetative period and for the winter season. The missing data for the vegetative period totalled about 11% (924 over 8640 data points). In this case we used the light response curves of the forest to interpolate missing data during the daytime and the respiration temperature relationship for the night-time conditions.

In Fig. 3 the trends of light responses for the beech forest from May to September are presented. The net carbon dioxide flux density is considered positive for

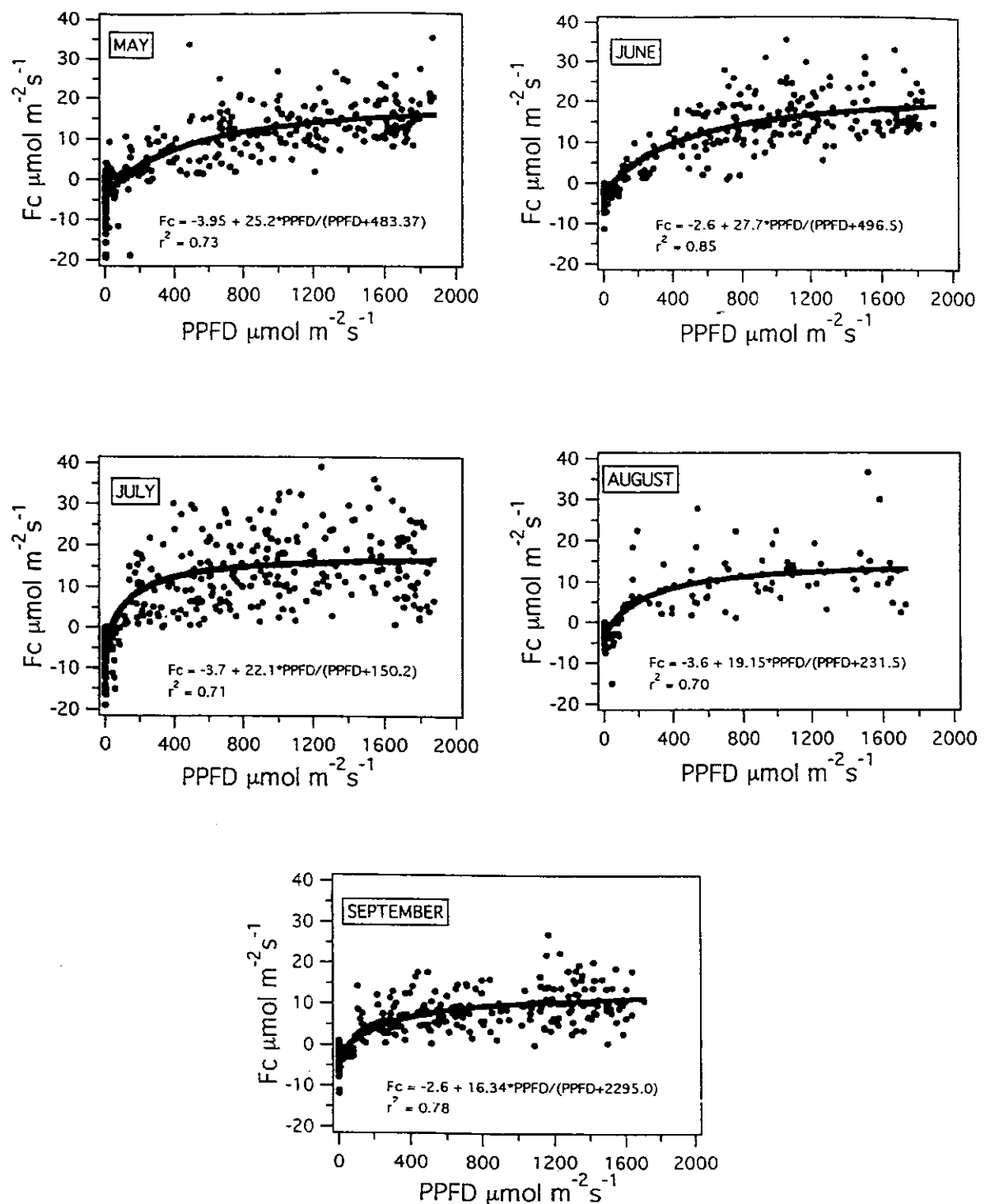


Fig. 3 Light response curves for the beech forest during the season from May to September 1993. Regression curves and correlation coefficients are also indicated.

uptake and negative for release. The equation used is a rectangular hyperbola which gives r^2 coefficients ranging from 0.70 to 0.85. All the relationships show a significant scatter of data. This behaviour is rather typical of eddy

flux data and can be caused by several factors among which the turbulent nature of the data, the interactive response of the canopy to various environmental factors and, above all, the frequent changes of footprint source

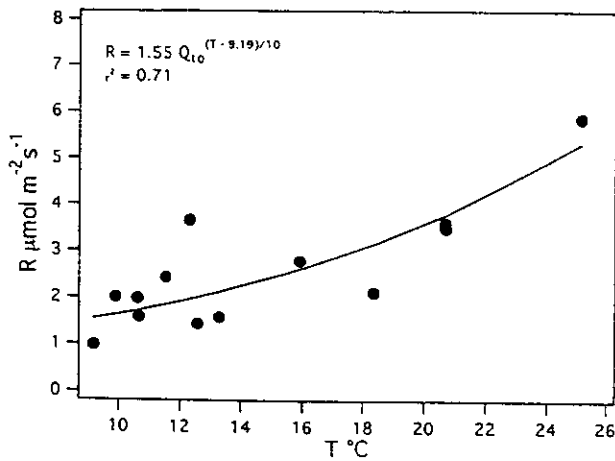


Fig. 4 Relationship between mean air temperature and respiratory fluxes along the season, with a Q_{10} of 2.17.

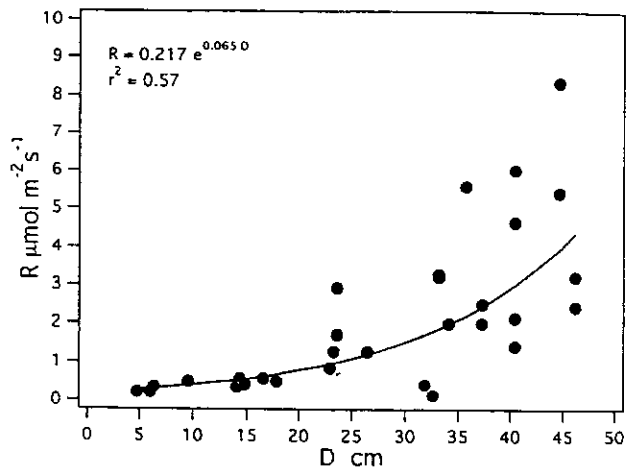


Fig. 5 Relationship between stem respiration and diameter.

area (see Moncrieff *et al.*, 1996, this issue, p. 231) are the most relevant.

However, the maximum scatter observed in July and August might be due to water stress conditions when VPD and water relations mainly drive the carbon dioxide exchange rates, even at high light irradiance. In September, water conditions return to a favourable level (after 260 mm of rain) and the scatter reduces.

The curvilinear shape of the light response is evident but the achievement of a saturating maximum, especially for May, June and September data, is not observed. Ruimy *et al.* (1995) discussed extensively the shape of a number of light response curves of different vegetation types. The conclusion was that forests and crops have more curvilinear responses than grasslands, a result confirmed also by Valentini *et al.* (1993) on a Californian grassland. Despite the curvilinear shape, the light response in unstressed conditions for this forest is not fully saturating even if the LAI at the season peak was 3.5 (see also Fig. 8), indicating a complete canopy closure. This result agrees with Ruimy *et al.* (1995) which indicates nonsaturating conditions for all the vegetation types.

In order to interpolate missing data during night-time, a relationship between average night-time F_c values and air temperature through the season was considered (Fig. 4). Each point of the graph represents the night-time respiration averaged over a period of 15 days. The same relationship was used to infer daytime respiration for calculating a total respiration budget.

As reported by many authors (see, for example, Greco and Baldocchi, 1996, this issue, p. 159) night-time fluxes measured by eddy covariance often fail to give a clear trend with temperature and show unpredictable fluctuations. There is a need of understanding better the turbulent fluxes in the nocturnal boundary layer and the limitations of frequency response of the current IRGA

analysers. However, using longer term averaging we arrived to an exponential relationship with a Q_{10} of 2.17. This Q_{10} value is smaller than the frequently reported by several authors of 2.5–3.0 (Amthor 1989) but within the range of the observed values.

The respiratory losses during the dormant season were estimated by measurements of stem and branch respiration by means of cuvettes and an IRGA analyser. Indeed it was not possible to scale the respiration-temperature relationship derived for the growing season to the winter period, due to the presence of a continuous snow cover.

While gaseous fluxes through snow cover have been observed (Sommerfeld *et al.* 1993), in our case direct measurements with cuvettes indicated zero CO₂ flux from the soil (Dore 1995). We are not in a position to exclude a possible CO₂ flux under different conditions; however, in the present work we have considered that the only source of CO₂ during snow cover conditions is represented by the wood biomass.

Stem and branch respiration is the sum of maintenance and construction components which are affected by the size and age of the material. For this reason we used the diameter as an index for these two influencing factors.

In Fig. 5 the relationship of stem respiration with diameter is presented. Respiration increases with diameter and we used the distribution in diameter classes of the tree population to estimate the respiratory losses of the entire ecosystem. In Fig. 6 the relationship of biomass respiration with temperature is presented: a good correlation coefficient was not obtained with a Q_{10} -type equation, but the use of a normal power equation yielded a better fit as indicated by the value of r^2 (0.91). Respiration data in this graph refer to ground area, after scaling to the population.

The eddy flux data (indicated by open circles in Fig. 6)

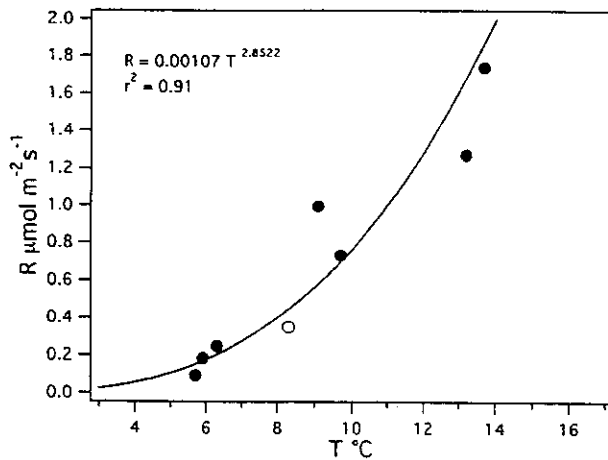


Fig. 6 Relationship between biomass respiration, expressed on a ground base area, and temperature. Eddy fluxes data during day December 15th are presented as an open circle.

obtained during snow cover on 15 December showed an average respiratory loss of $0.35 \mu\text{mol m}^{-2} \text{s}^{-1}$ at an average temperature of 8.3°C , which agrees well with the estimated respiration from cuvette measurements. This observation, even if not repeated through the winter, indicates that our assumption concerning a negligible carbon dioxide flux from the soil can be taken as valid.

Combining measurements of the net carbon dioxide flux density during the growing season and the estimation of respiratory components during winter by cuvette measurements and temperature scaling, we arrive at the annual trend of the net ecosystem production (NEP) of the forest ecosystem, presented in Fig. 7.

Each datum represents a value integrated over a 15-day period, expressed as grams of carbon per square metre of ground. The peak occurs in late June (100.5 g C m^{-2}), while it is evident that the decrease of the net carbon exchange in late July – beginning of August (22 g C m^{-2}) and subsequent increase at the end of August (45.1 g C m^{-2}), are due to the beginning of rainfall after a period of drought. The effect of drought is rather significant since the total flux reaches about 22% of the peak value and recover only partially after precipitation (45% of the peak value).

In Fig. 8 the trend of leaf and stem area index (LAI + SAI) is presented for the year, as measured by the intercepted radiation. The leaf area index can be estimated by subtracting a value of SAI of 1. Leaf area index reached 3.5 at the beginning of June and remained almost constant from late August (3.7) until the beginning of October where it starts to decline (2.5). Leaf fall is completed by the beginning of December. An independent estimate of LAI by basket harvesting showed a value of 4.2 at the end of the season, which is close to the one derived from

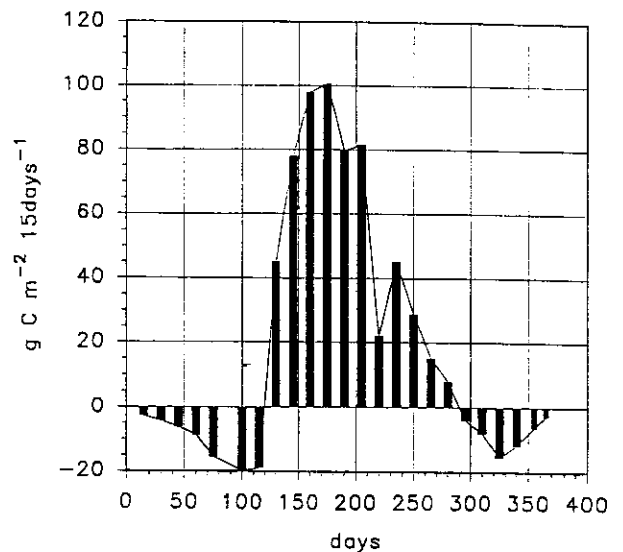


Fig. 7 Annual trend of the Net Ecosystem Production measured by net carbon dioxide exchanges and interpolation of missing data. Each data point refers to a 15 days integrated value.

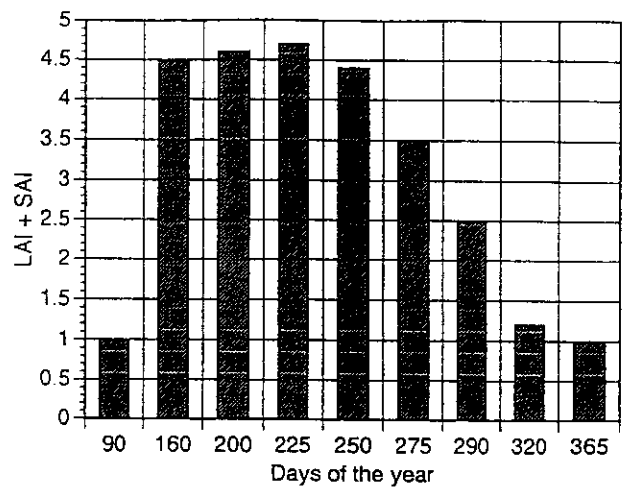


Fig. 8 Annual trend of Leaf and Stem Area Index ($\text{m}^2 \text{ leaf} + \text{wood m}^2 \text{ ground}$) measured by intercepted radiation.

intercepted radiation. The total net ecosystem production for 1993 was $472 \text{ g C m}^{-2} \text{y}^{-1}$.

In Fig. 9 the cumulated trend of gross ecosystem production (GEP, $\text{NEP} + \text{R}$) is presented together with the cumulated ecosystem respiration losses (R). GEP at the end of the year reached $1016 \text{ g C m}^{-2} \text{y}^{-1}$ and respiration was $544 \text{ g C m}^{-2} \text{y}^{-1}$. In Table 2 there is a summary of the carbon balance components measured by eddy covariance (eddy) and by direct sampling (samp).

The above-ground NEP, estimated by biomass sampling, under the assumption of negligible leaf litter accumulation, is $238 \text{ g C m}^{-2} \text{y}^{-1}$, that is about 50% of

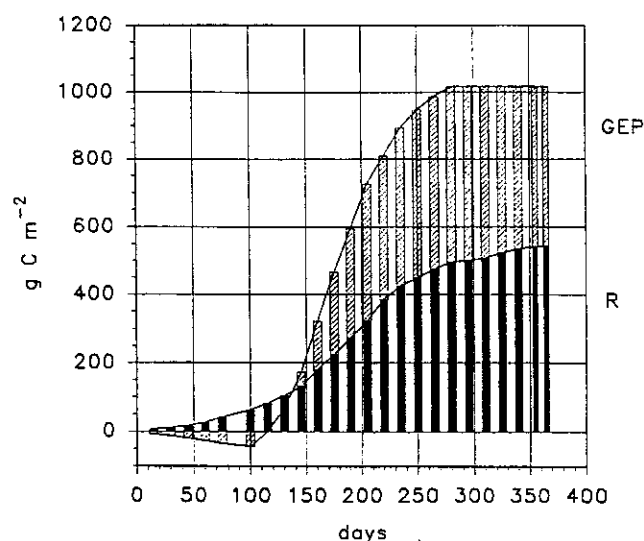


Fig. 9 Cumulative trend of Gross Ecosystem Production (GEP) and Respiration (R) for the year.

Table 2. Carbon balance components of the forest. NPP, all expressed as $\text{g C m}^{-2} \text{y}^{-1}$.

NEP _{eddy}	NPP _{samp}	GEP _{eddy}	R _{eddy}	WI _{samp}	LP _{samp}	FRP _{samp}
472	802	1016	544	238	107	457

NEP_{eddy}, Net Ecosystem Production, measured by eddy covariance seasonal fluxes and interpolation of missing data; NPP_{samp}, Net Primary Production determined by direct sampling of wood increment, leaf production and roots turn-over; GEP_{eddy}, Gross Ecosystem Production estimated by NEP_{eddy} + R_{eddy}; R_{eddy}, Ecosystem Respiratory losses, estimated by eddy covariance and interpolation of missing data; WI_{samp}, Wood increment by direct sampling; LP_{samp}, Above-ground litterfall by direct sampling; FRP_{samp}, Fine roots (0–5 mm) production by direct sampling (0–45 cm)

the total NEP, indicating a significant below-ground carbon accumulation.

A similar below-ground accumulation has been reported by Greco & Baldocchi (1996, this issue, p.159), where below-ground NEP accounted for 68% of the total NEP measured by eddy covariance.

Other explanations of the observed difference between total and above-ground NEP, measured by eddy covariance and direct sampling, respectively, are:

- 1 the eddy covariance total NEP is overestimated since we were not able to measure adequately nighttime respiratory fluxes;
- 2 our assumptions of negligible carbon dioxide flux during snow cover conditions is wrong even if confirmed by our limited experiments;
- 3 there is a significant growth of large roots (> 5 mm) which is not taken into account in our NPP estimate.

The problems associated with the use of eddy covariance in inferring annual carbon gain are well addressed by Moncrieff *et al.* and Goulden *et al.* (this issue, pp. 231 and 169ff.), but further experiments are still needed to clarify the effects of atmospheric stability particularly during nighttime conditions.

So far show typical errors taken into account that eddy covariance estimates can be accurate in general up to $\pm 20\%$. This error tends to decrease with increasing statistics of data.

Carbon dioxide efflux from the snow-covered soil was considered negligible in the present study. Our limited experiments carried out with cuvettes and eddy flux measurements during snow cover conditions confirmed this assumption. However, if we take the maximum CO₂ fluxes presented by Sommerfeld *et al.* (1993), who measured CO₂ fluxes through Wyoming snowpack, and extrapolate them to our winter season, then we arrive at a respiratory flux of $86 \text{ g C m}^{-2} \text{y}^{-1}$, which represents about 20% of our total net ecosystem exchange. Thus the problem of a significant below-ground carbon accumulation remains, even taking into account CO₂ diffusion through the snowpack.

It is interesting to compare this eddy covariance estimate of the total NEP value with the existing literature. Lieth and Whittaker (1975) show for temperate forests a NPP ranging from 300 to $1100 \text{ g C m}^{-2} \text{y}^{-1}$ with a mean value of $550 \text{ g C m}^{-2} \text{y}^{-1}$. A recent review by Ruimy and Saugier (1994) indicates values ranging from 100 to $900 \text{ g C m}^{-2} \text{y}^{-1}$ with a mean value of $300 \text{ g C m}^{-2} \text{y}^{-1}$.

NEP estimated by eddy covariance and NPP cannot be directly compared, since the latter also includes heterotrophic respiration, a component which is by definition already subtracted in the NEP. Thus NEP should always be smaller than NPP, due to detritus decomposition.

NPP for the study forest, estimated through biomass sampling, is $802 \text{ g C m}^{-2} \text{y}^{-1}$, considering fine root production on the 0–45 cm soil profile. This value is slightly higher than the mean estimates of both Lieth and Whittaker (1975) and Ruimy and Saugier (1994), but closer for example to other estimates related specifically to beech forests. Values of total NPP for beech forests range from 645 to $950 \text{ g C m}^{-2} \text{y}^{-1}$ (Reichle 1981).

Since there are not many studies of NEP by direct measurement it is not easy to adequately check the eddy covariance estimate. Greco & Baldocchi (1996, this issue, p.159) found for a mixed deciduous forest in Tennessee a net carbon gain of $525 \text{ g C m}^{-2} \text{y}^{-1}$, while Wofsy *et al.* (1993) found for the Harvard forest a net carbon exchange of about $220 \text{ g C m}^{-2} \text{y}^{-1}$. Our value ($472 \text{ g C m}^{-2} \text{y}^{-1}$) is intermediate between the two, but closer to the Oak Ridge forest which also has a similar climate.

If we assume that both the eddy covariance NEP and direct sampling NPP values are correct, or affected by

negligible errors, the amount of heterotrophic respiration appears not to decompose totally the annual litterfall (leaves + roots litterfall), producing a net accumulation of organic matter in the soil or in living roots. Furthermore this accumulation, which is $234 \text{ g C m}^{-2} \text{ y}^{-1}$, represents about 50% of the total NEP.

This result can be explained by the fact that this forest is under an active regrowing phase and represents a southern boundary for beech diffusion in Europe. For this reason the ratio of below-ground – above-ground productivity of this ecosystem is 1.4, a rather high value if compared with other Central Europe beech ecosystems (Reichle 1981). The high value can be explained by the great investment of carbon in roots needed to overcome periods of water stress, which are typical of the Central – South Italy region.

At the moment we are not able to discriminate how much carbon is allocated in living roots (diameter greater than 5 mm) or in soil organic matter and this problem will be addressed in future studies.

Conclusions

The eddy covariance technique is a powerful tool to estimate directly the annual net ecosystem production (NEP) of terrestrial ecosystems. Indeed most of the data available on productivity concern NPP (mainly above-ground), while global estimates of NEP are needed to address the problem of the carbon missing sink. Thus it is important to increase our data on NEP for different ecosystems, through implementation of eddy covariance stations and by increasing our knowledge of carbon fluxes. However, as with eddy covariance data, recovery and interpolation is always needed for completing the annual cycle. Furthermore a thorough error analysis is needed to interpret the eddy covariance data.

The problem of atmospheric stability, particularly during night-time conditions, and analysers frequency response need to be urgently investigated to provide a first estimate of the errors involved in an annual carbon budget study. Measurements of NEP *per se* are important as a first step towards understanding the carbon sequestering potential of terrestrial vegetation, but are also necessary to further investigate the processes which drive carbon fluxes and pool and within the ecosystem.

Carbon accumulation in the soil, for example, can be an important process which deserves to be studied more intensively. For this reason a combination of eddy covariance fluxes and biomass sampling can be an effective strategy in providing useful information on the impact of vegetation structure and management on carbon conservation.

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