Annual and monthly carbon balance in an intensively managed Mediterranean olive orchard

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Abstract

At present, research activities on the role of orchard systems in sequestering atmospheric CO_2 remain scarce. This paper aimed to contribute to assessing the carbon balance of a Mediterranean olive (*Olea europea*) orchard. The net ecosystem exchange, the ecosystem respiration and the gross primary production were computed for two consecutive years through eddy covariance, and the different biomass accumulation terms were also inferred in the same period through an inventorial method. The net carbon exchange ranged from 13.45 t(C) ha^{-1} year^{-1} to 11.60 t(C) ha^{-1} year^{-1}. Very similar values [12.2 and 11.5 t(C) ha^{-1} year^{-1}] were found with the direct carbon accumulation inventory. The intensive farming management (irrigation included) and the young age of the plants (12–16 years old), still in an active growing phase, led the olive plantation to be a higher carbon sink with respect to other evergreen orchards reported in the literature.

Additional key words: carbon balance; eddy covariance; net ecosystem exchange; olive orchard.

Introduction

The potential role of crops in meeting carbon reduction goals such as in the Kyoto Protocol and, in the road ahead, to improving knowledge about the attitude of evergreen orchard ecosystems in absorbing atmospheric carbon dioxide is still an open issue. Photosynthetic carbon uptake data are essential for proper implementation of Life Cycle Assessment (LCA), now used to quantify the environmental impacts of greenhouse gas in the whole production chains (Grunberg *et al.* 2010 Kilpelainen *et al.* 2011).

Describing the dynamics of ecosystem functioning is also crucial for assessing ecosystem services (Watanabe and Ortega 2011), for estimating and simulating exchange drivers (Beringer *et al.* 2011) and, to a great extent, for understanding climate regulation and climate change. In recent years, the Fluxnet network has recorded many studies of exchanges of carbon dioxide, water and heat with a latitude distribution between 70°N–30°S, principally in temperate conifer and broadleaved deciduous and evergreen forests, short crops, grasslands, wetlands and the tundra.

The net carbon and water exchanges in such agricultural systems as orchards have been so far mainly studied with carbon stock methods and, hence, following monitoring procedures that often lack validation. The carbon balance assessment in managed agricultural systems is still biased by many uncertainties because very few micrometeorological towers operate in orchards or other cultivated crops. Agricultural carbon balance assessments are also under the constraints of finding homogeneous extensions to match fetch requirements.

Orchards, similarly to all horticultural crops, are

strongly affected by human actions. Different locally adopted management and farming techniques are capable of strongly influencing plant physiology and consequently modifying carbon exchange efficiency. Genotypic differences among cultivars with different geographic origins may add variability to the photosynthetic response within the same species, as observed in olive trees by Bacelar *et al.* (2009).

Biodiversity is much lower than in natural forests, thus affecting soil biological activity and respiration; nutrients are supplied and not limited; and agricultural management practices such as pruning reduce plant to plant competition for light and water. When the orchard is irrigated, as it is the case in many Mediterranean areas, the summer water stress that may strongly reduce carbon assimilation from the canopy is avoided or strongly limited (Smith 2004). Unlike annual crops, orchards for fruit production are able to sequester C for a lifetime period of at least 20–25 consecutive years, with small annual fluctuations (Liguori *et al.* 2009). The role of orchards as efficient atmospheric carbon sinks is also favoured by vigorous growth (although dependent on the adopted rootstocks and the practiced soil management) and by high leaf area densities.

The information characterising orchard abilities to sequester carbon must also consider evergreen and deciduous fruit trees: it is intuitive that evergreen species (such as olive, orange, and lemon) may constitute a better C sink due to their year round activity. For intensive deciduous orchards, Tagliavini *et al.* (2008) have observed in apple an NPP value of 4.7 t(C) ha^{-1} year^{-1}, and Montanaro *et al.* (2008) observed a value of 5.1 t(C) ha^{-1} year^{-1} in peach. Rossi *et al.* (2007) measured a net ecosystem exchange (NEE) of 3.09 t(C) ha^{-1} year^{-1} during the vegetative period in a kiwifruit field. For evergreen species, Liguori *et al.* (2009) reported a net primary production (NPP) of 6.9 t(C) ha^{-1} year^{-1} for the low density traditional orange orchard system and 7.1 t(C) ha^{-1} year^{-1} for the high density intensive system. In these orange orchards, NEE was calculated as 2.4 t(C) ha^{-1} year^{-1} and 3.3 t(C) ha^{-1} year^{-1}, respectively.

The farming community now accepts the concept of high quality production for certain crops, characterised by strong linkages with the territory and by providing several innovative paths for growing traditional crops. Several major technological changes have been adopted in the olive management systems over the last decades. The traditional low density (lower than 100 trees/ha), rain fed orchard, with low inputs of fertilizer and pesticides and manual harvests, has been gradually replaced by intensive (200–400 trees/ha) drip irrigated systems, with reduced tillage and intensive mechanised cultivation (Villalobos *et al.* 2006). Such a technological innovation has increased single tree ecophysiological activity and structural orchard carbon sequestration potential, driving toward positive repercussions in productivity (Pernice *et al.* 2009).

Our case study was an intensive advanced production model, where for centuries soil and climate characteristics have provided the best environmental conditions for olive growth in this important Mediterranean region. This crop has been historically part of the agronomical, social and economic substrate of the area as one of the most important agricultural product, prominent for landscape added value and profit to farmers.

Materials and methods

Site: The measurements were carried out in an olive orchard (cv. Nocellara del Belice) located in Castelvetrano (37°38'40''N, 12°50'47''E, Italy). The site is part of the Italian CARBOITALY network (http://www.europe-fluxdata.eu/newtcdc2/ carboitaly_home.aspx) within the European CARBOEUROPE frame (http://www.carboeurope.org/).

The orchard covered approximately 11 ha and was formed by four different plots (A, B, C, D) characterised by different tree ages and planting densities (Fig. 1). Orchard and tree characteristics (height and canopy diameter averaged on 15 trees of each plot) and leaf area index (LAI) are summarised in Table 1. Tree height was approximately 4 m.

The soil texture was clay loam, with volumetric water content at field capacity of 36.1% and 17.4% at −1.5 MPa soil water potential. In accordance with the cultural practices adopted in this traditional olive growing area, soil wass clean cultivated during the vegetative season,
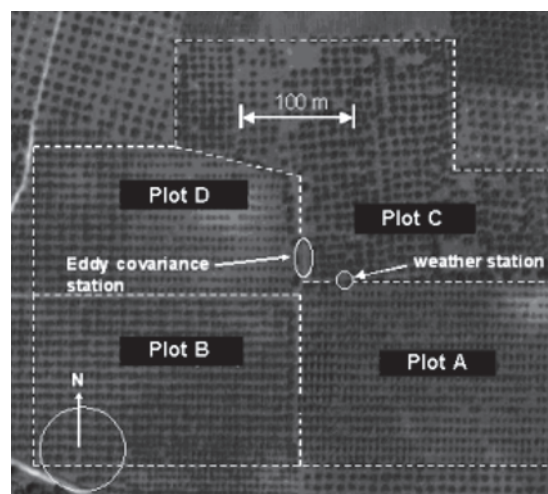

Fig. 1. Map of the orchard indicating different plots, their compass position and the layout of the sensors.

Table 1. Orchard characteristics and tree phytometric parameters. LAI – leaf area index.

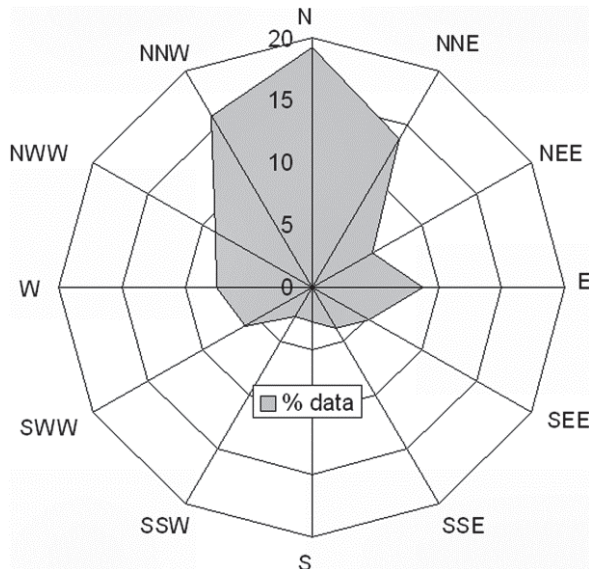| Plot	Age [years]	Tree spacing [m]	Tree height [m]	Trunk cross sectional area [cm^2]	LAI	Area of the plot [ha]
A	12	5 × 8	3.7 ± 0.2	321 ± 8	3.4 ± 0.1	2.57
B	16	5 × 8	3.5 ± 0.1	463 ± 41	3.0 ± 0.1	2.48
C	150	7 × 7	3.4 ± 0.2	873 ± 83	3.0 ± 0.1	3.69
D	12	5 × 8	3.7 ± 0.2	225 ± 19	2.6 ± 0.1	2.15

Fig. 2. A wind rose for a 10° wind sector expressed as a percent of the data over a 5-year period.

with no weed control performed during the autumn and winter, when natural cover crops grow.

All of the plots were equipped with an irrigation system consisting of two micro sprinklers (8 l h^{-1}) per tree. The total volume of water applied during the summer was fixed at 2,000 m^3 ha^{-1} and added to precipitations amounts.

Phytometric parameters (a tree height, a canopy diameter) were derived by analysing two pictures (taken from two different perspectives) per 5 trees of any plot. The tree height and canopy diameter were referenced to a known size object and calculated with a computer imaging program (*ImageTool*, University of Texas**,** USA) (Wilcox *et al.* 2002). Mean trunk cross sectional area was derived for 40 trees for each plot by measuring the trunk circumference at 40 cm from the ground.

Leaf area index (LAI) was measured by an *LAI-2000 Plant Canopy Analyzer* (*Li-Cor Bioscience*, USA). The total tree leaf area determination was carried out by "ideally" splitting, on the horizontal plane, the canopy into four quadrants, sequentially measuring the leaf area index of each of them and averaging the observations. In plots A and C, the tree leaf area was also determined by directly multiplying canopy land area projected on the ground (m^2) for tree leaf area index (m^2 m^{-2}).

Meteorological and micrometeorological instrumentation and calculations: The vertical fluxes of CO_2 and H_2O were measured at the orchard scale using eddy covariance (Swinbank 1951, Aubinet *et al.* 2000, Baldocchi *et al.* 1988) for two consecutive years (from July 2006 to June 2008).

An 8-m mast set up equipped with a 3-dimensional sonic anemometer (*CSAT-3D, Campbell Sci.*, USA) and an open path infrared absorption gas analyser (IRGA) (*Li7500, LiCor Inc.*, USA) was positioned in the orchard as shown in Fig. 1. On the same mast, a net radiometer (*NR Lite, Campbell Sci.*, USA) was placed at the same height to measure the net available energy at the surface. The soil heat flux was computed through three flux plates (*HFP01, Campbell Sci.*, USA) installed at a depth of 5 cm at three different points at the same distance from the base of the mast.

Wind, water vapour, carbon dioxide, and temperature were sampled at 10 Hz, and the data were stored on a *CR1000* (*Campbell Sci.*, USA) data logger.

Air temperature, wind speed and direction, relative humidity, pressure, incoming global radiation and precipitation were measured by an automatic weather station located near the orchard (500 m northeast) and managed by the regional Agrometeorological Information Service (SIAS). The wind data recorded from this station for the time period 2002–2006 were considered when setting up the tower, with the prevailing wind directions determined to be northeast and northwest (Fig. 2).

The eddy covariance measurement system and the data processing followed the guidelines of the standard EUROFLUX rules (Aubinet *et al.* 2000).

A data quality check was applied during the post processing together with some routines to remove the common errors: running means for detrending, three angle coordinate rotations and despiking. Stationarity and surface energy balance closure were also checked (Kaimal and Finnigan 1994).

As shown in Table 1, the orchard included a plot of differently aged trees (150 years old, plot C). This condition was consistent with the regional scenario based on the reconversion of traditional olive plantations. Our concern was to assess how this nonhomogeneous source sink distribution could misrepresent a proper flux monitoring. Thus, a statistical analysis was performed to quantify the annual percentage of flux data coming from plot C and contributing to the total flux.

As remarked by Aubinet *et al.* (2000), the major errors in calculating fluxes may occur during the nocturnal stable atmospheric conditions. To minimise this effect, the storage of CO_2 within the canopy was estimated with the time change in the CO_2 concentration measured at the top of the mast (Greco and Baldocchi 1996):

$$F_{\Delta S} = \frac{\Delta C(z)}{\Delta t} \Delta z \qquad (1)$$

where $\Delta C(z)$ is the change in CO_2 at the height z, Δt is the time period, and Δz is the height of measurement.

To avoid underestimating the nocturnal surface exchanges (Moncrieff *et al.* 1996, Aubinet *et al.* 2000, Falge *et al.* 2001), the night data were carefully inspected to detect invalid values (*i.e.*, negative values of carbon dioxide flux or values of respiration outside of the trend). Such a procedure was preferred over the more usually adopted correction based on an established threshold u_* (friction velocity) value because of the regular structure of the orchard orography and the sparse arrangement of trees.

Data quality check procedures and some occasional failure of the system led to a data coverage of 66% of the whole period. Therefore, a procedure of data gap filling was adopted to compute the annual and monthly NEE. When the gaps were smaller than three consecutive hours, data were linearly interpolated. In all the other cases, the non linear regression method was applied (Falge *et al.* 2001). Missing values of CO_2 flux (F_c) were calculated using the regression relationships established between Fc and measured temperature (nightime) and radiation (daytime) on monthly bases.

As far as nocturnal respiration fluxes are concerned, the Lloyd and Taylor (1994) relation was applied:

$$R_e = b_1 \, e^{b_2 \, T_{air}} \qquad (2)$$

where R_e is the ecosystem respiration and b_1 and b_2 are the coefficients computed for each month from the experimental data (Table 2).

The great variability occurring in the parameterisation coefficients demonstrated how the nocturnal respiration in the orchard varied during the year due to changes in meteorological conditions and plant phenology.

For daytime C fluxes, the light response equation (Dagnelie 1991) was used:

$$F_c = GPP_{OPT} \left(1 - e^{\frac{a\,PPFD}{GPP_{OPT}}} \right) - R_{day} \qquad (3)$$

where PPFD is the photosynthetic photon flux density, a is a coefficient, GPP_{OPT} is the gross primary production and R_{day} is the diurnal ecosystem respiration. In this case, the diurnal measurements of CO_2 flux for each month

during the whole measurement period were parameterised as:

$$F_c = b_1 \left(1 - e^{-b_2\,PPFD} \right) - b_3 \qquad (4)$$

with the obtained coefficients reported in Table 3. The coefficient b_1 is the gross primary production and records the highest values during the summer months. The b_3 parameter represents the mean diurnal ecosystem respiration, and its values show a high degree of variability and b_2 is a simple parameterization coefficient.

An unexpected failure of the flux system occurred during an entire month (February 2007). In this case, very similar meteorological conditions occurred in January, so we were able to carry out the gap filling using, in the Eqs. 2 and 4, the same parameterisation coefficients as the month before.

Total carbon exchange terms were estimated both at monthly and annual scales. The NEE was computed from the complete series of the CO_2 fluxes measured by eddy covariance and gap filled using the nonlinear regression method described above. The ecosystem respiration (ER) was estimated according to Falge *et al.* (2001), where the Lloyd and Taylor's equation values are reported in Table 2. The gross primary productivity (GPP) for each 30 min period was the difference between NEE and estimated ER.

Table 2. Coefficients of CO_2 flux (b_1) and air temperature (b_2) obtained by applying Lloyd and Taylor's (1994) parameterization throughout the whole measurement period. The statistical significance is for all regression curves $p < 0.05$.

Month	b_1 [μmol m^{-2} s^{-1}]	b_2 [°C^{-1}]	R^2
July'06	0.9 ± 0.3	0.05 ± 0.01	0.78
August'06	2.5 ± 0.1	0.012 ± 0.001	0.97
September'06	0.6 ± 0.2	0.07 ± 0.02	0.71
October'06	1.7 ± 0.2	0.053 ± 0.006	0.96
November'06	2.0 ± 0.4	0.04 ± 0.01	0.79
December'06	0.9 ± 0.1	0.08 ± 0.01	0.97
January'07	0.8 ± 0.2	0.11 ± 0.03	0.88
February'07	-	-	-
March'07	1.3 ± 0.4	0.09 ± 0.02	0.92
April'07	1.08 ± 0.07	0.092 ± 0.005	0.98
May'07	1.2 ± 0.3	0.05 ± 0.01	0.90
June'07	2.8 ± 0.1	0.015 ± 0.003	0.87
July'07	0.9 ± 0.2	0.04 ± 0.01	0.79
August'07	1.8 ± 0.3	0.012 ± 0.007	0.63
September'07	0.7 ± 0.3	0.07 ± 0.02	0.81
October'07	1.4 ± 0.3	0.06 ± 0.01	0.88
November'07	0.8 ± 0.2	0.13 ± 0.01	0.97
December'07	2.0 ± 0.1	0.053 ± 0.005	0.98
January'08	0.9 ± 0.4	0.11 ± 0.02	0.93
February'08	1.4 ± 0.5	0.07 ± 0.03	0.85
March'08	1.4 ± 0.1	0.071 ± 0.008	0.98
April'08	1.23 ± 0.03	0.064 ± 0.002	0.99
May'08	0.73 ± 0.09	0.092 ± 0.006	0.98
June'08	0.9 ± 0.3	0.05 ± 0.01	0.93

Table 3. Coefficients of CO_2 flux (b_1) and PPFD (b_2, b_3) obtained by applying Dagnelie (1991) parameterization for each month of the whole measurement period. The statistical significance is for all regression curves $p < 0.05$.

Month	b_1 [μmol m^{-2} s^{-1}]	b_2 [μmol m^{-2} s^{-1}]	b_3 [μmol m^{-2} s^{-1}]	R^2
July'06	−24 ± 1	0.0004 ± 0.0001	−2.0 ± 0.6	0.61
August'06	−22 ± 2	0.0005 ± 0.0001	−1.6 ± 0.4	0.61
September'06	−30 ± 4	0.0012 ± 0.0001	−0.9 ± 0.6	0.67
October'06	−38 ± 2	0.0021 ± 0.0003	−4.8 ± 0.9	0.71
November'06	−20 ± 1	0.0014 ± 0.0002	−1.7 ± 0.7	0.68
December'06	−20.4 ± 0.9	0.0017 ± 0.0002	−1.4 ± 0.5	0.69
January'07	−22 ± 1	0.0013 ± 0.0002	−1.5 ± 0.6	0.61
February'07	-	-	-	-
March'07	−29 ± 2	0.0023 ± 0.0006	−2.3 ± 0.5	0.60
April'07	−29 ± 1	0.0021 ± 0.0002	−4.3 ± 0.7	0.71
May'07	−23 ± 1	0.0021 ± 0.0003	−2.8 ± 0.8	0.67
June'07	−31 ± 3	0.0011 ± 0.0001	−3.0 ± 0.4	0.76
July'07	−37 ± 4	0.0009 ± 0.0002	−2.3 ± 0.3	0.67
August'07	−35 ± 3	0.0008 ±0.0001	−0.8 ± 0.3	0.69
September'07	−33 ± 7	0.0010 ± 0.0003	−2.2 ± 0.5	0.58
October'07	−23.2 ± 0.9	0.0032 ± 0.0004	−4.89 ± 0.6	0.64
November'07	−24 ± 1	0.006 ± 0.001	−5 ± 1	0.61
December'07	−27 ± 3	0.0006 ± 0.0001	−0.7 ± 0.2	0.61
January'08	−28 ±2	0.0033 ± 0.0007	−5 ± 1	0.64
February'08	−35 ± 4	0.0010 ± 0.0004	−2.6 ± 0.6	0.64
March'08	−26 ± 3	0.0007 ± 0.0001	−1.1 ± 0.7	0.61
April'08	−41 ± 4	0.0005 ± 0.0001	−0.5 ± 0.1	0.66
May'08	−39 ± 7	0.0009 ± 0.0001	−2.78 ± 0.3	0.80
June'08	−46 ± 2	0.0006 ± 0.0001	−1.3 ± 0.6	0.69

Estimation of biomass accumulation: The capacity of orchard to store CO_2 was directly analysed by estimating the biomass production in above- and belowground components with the inventorial method. The amount of vegetation removed by winter pruning, increased trunk cross sectional area and cover crop biomass were directly measured. Other components (senescent leaves, root biomass and olive and oil production) were measured or estimated to complete the analysis.

As a common horticultural practice, winter pruning was applied yearly to reduce natural tendencies of olive trees to alternate bearing, and it maintained values of LAI not higher than 3. The dry matter accumulated and removed by winter pruning was estimated from 15 trees belonging to plot A (younger trees) and 10 to plot C (older trees). The winter pruned biomass of each tree was related to its trunk cross sectional area (calculated on 30 randomly chosen plants for each plot) to extrapolate the results to the whole plots. Part of the freshly pruned biomass (30%) was divided into wood, shoots and leaves to calculate the specific dry matter content of each compartment. The determination of dry matter was carried out on sub samples dried to constant mass at 70°C in a forced oven chamber. The determination of carbon that accumulated in the canopy was completed by also including the natural turnover of leaves, which normally renew in 2 or 3 years (Villalobos et al. 2006).

The amount of carbon stored in trunks was deter-mined on the same trees by calculating the annual increase of their circumference: this value was measured with a flexible tape positioned at 30 cm from the ground. Considering the mean trunk girth, the annual wood volume increment for each plot was calculated following a geometric assimilation assumption (Campbell and Norman 1990).

The production of 20 trees, randomly chosen in plots A and C, was weighed to determine the amount of C accumulated in the crop yield, either as oil or husk (olive residues). A sub sample (10% of the total fresh mass) was processed to quantify oil yield.

The root length densities (RLD) were measured using the auger sampling method (Mac Dicken 1997). An auger of 12.5 cm^2 ID (inner area) was used, taking samples in linear transects (sampling every 80 cm) positioned in the intra- and inter-row space. Soil samples were taken at layers of 0–15, 15–30 and 30–60 cm (Bohm 1979, Jackson et al. 1996). To better separate the roots from the soil, each sample was immersed in a saturated NaCl solution for 24 h (Tardieu and Manichon 1986). Roots were washed and weighed. Root length was measured using a common 1 mm precision ruler. RLD was ex-pressed in centimetres of root length per cubic centimetre of soil.

The adopted soil tillage during the year allowed the growth of spontaneous annual weeds, characterised by the prevailing presence of Graminaceae species. The

accumulation of C in this covercrop was calculated by measuring its LAI (*LI-COR LAI 2000, LiCor Inc*., USA) and then harvesting its entire biomass (including roots) in 6 randomly chosen sampling areas (6 m^2 each, 3 in plot A and 3 in plot C). Covercrops were weighted and dried to constant mass at 70 °C in a forced oven chamber.

Results

Flux calculation: The meteorological data of the site, typical of a Mediterranean area, are reported in Fig. 3. The homogeneity of the surface was the main basic constraint for a correct application of the eddy co-variance. The olive orchard was selected based on its area (11 ha) and of the better vegetation homogeneity of the surrounding area (mainly olive orchards), the very flat terrain and the satisfaction of the fetch requirements.

A footprint analysis was carried out over a one year period (July 2006–June 2007) following the methodology proposed by Schuepp *et al.* (1990). Fig. 4 shows the upwind distances most likely contributed to our measured
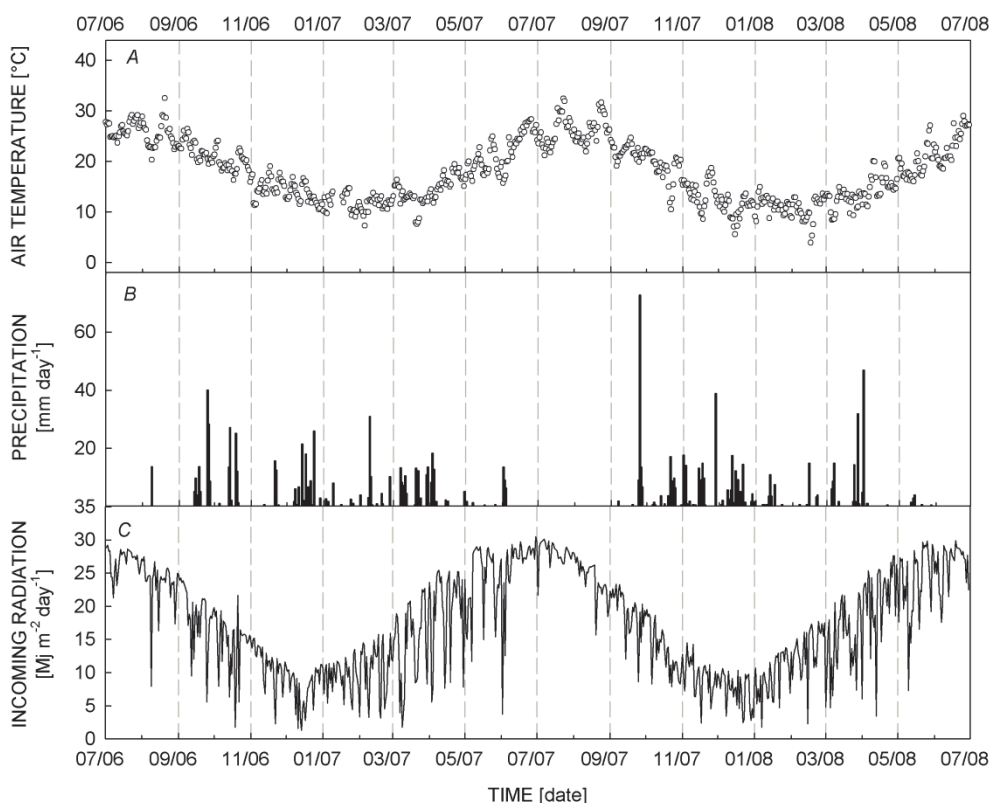

Fig. 3. Trend of two years of measurements of (*A*) daily mean air temperature, (*B*) daily cumulative precipitation, and (*C*) daily incoming radiation.

total fluxes. The fetch of the surface confirmed that the measurements were entirely within a well developed olive crop boundary layer and, thus, correctly expressed the local fluxes (Barkza *et al.* 2009). A large number of the dots concentrated in the northeast (NE) wind direction sector, where the centenary trees were located. To assess their relative contribution to total flux quantification, a further two year classification of wind direction was carried out (Table 4). Approximately 35% of wind events came from the NE direction, while 65% came from all other directions, where younger trees were grown. Within these percentages, the amount of daily data was only 22% for the NE direction. This allowed us to consider the relative contribution of old and less physiologically active trees as scarcely important to the total computation of orchard C flux (about 7.5% of the total).

Olea europea has been commonly grown in the Medi-terranean basin, where prolonged droughts occur mainly in the summer. This species has developed a series of physiological mechanisms, some of them common to several plants of the Mediterranean macchia, to tolerate drought stress and grow under hot and arid conditions. Although irrigated, this species has also shown low energy partitions in term of the latent heat flux of evapo-transpiration. During a typical day of a summer month (variations that were not relevant were found during the complete analysis), the percentage of available energy used for turbulent water exchange was slightly less than 20%, while approximately 53% was spent for surface atmosphere heat exchange and 17% was stored in the soil. Similarly as shown by Sofo *et al.* (2008), the adapta-tion to a high temperature and a low water consumption was also shown here. The orchard did not show any decreasing trends in daily photosynthesis, manifesting a
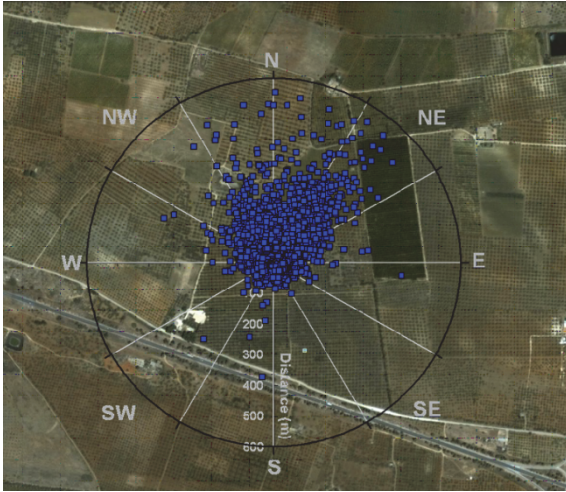
Fig. 4. Map of the orchard and soil use in the proximities of the eddy covariance station and footprint analysis. *Squares* indicate the distance from the maximum flux contribution at half hour scale. Data refer to a whole year.

Table 4. Percentages of CO_2 flux data as a function of wind direction for plot C and other plots during night- and daytime periods.

Plot C 35% of the total data		Other plots 65% of the total data	
Night	Day	Night	Day
78%	22%	58%	42%

very limited midday depression in the evapotranspiration (Fig. 5).

The energy balance closure, obtained by plotting net radiation (R_n) minus the soil heat flux (G) against the sum of the sensible heat flux (H_0) and the latent heat flux (λE), has been verified with half hourly values for the entire two years of measurements (Fig. 6). The correlation coefficients were confident ($R^2 = 0.90$, and 0.83).
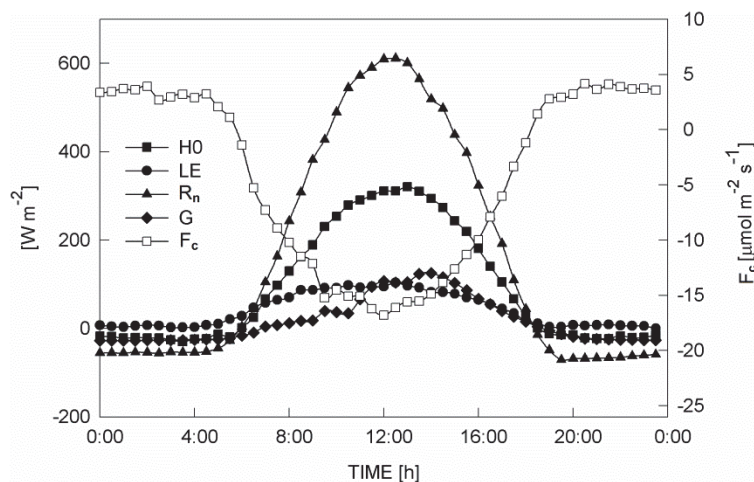
The closure deficit was approximately 15%. These results agree well with other eddy covariance applications above forest and crop systems (Goulden *et al.* 1996, Aubinet *et al.* 2000).

The net ecosystem exchange was calculated at monthly and annual scales. Fig. 7 shows the monthly NEE, ER and GPP together with the air temperature and the cumulative precipitation over two years of measurements.

The two July to June time periods taken to define the annual exchange activities of the orchard were characterised by some different patterns of precipitation and air temperature. The air temperature in the first year was consistently higher (annual mean: 18.2°C) than that in the second year (annual mean: 17.4°C). Additionally, the cumulative precipitation was slightly higher (678 mm *vs.* 634 mm). In the second year, approximately 60% of the total precipitation concentrated in the autumn, while almost no rain occurred in the summer.

Due to the evergreen nature of olive trees, the net CO_2 uptake occurred throughout the whole year. The highest NEE values were recorded during the spring and summer periods [120–170 g(C) m^{-2} month^{-1}]. ER ranged from 80 to 170 g(C) m^{-2} month^{-1}, reaching the highest value during the spring and the autumn.

The highest value of ecosystem assimilation (GPP) was 280 g(C) m^{-2} month^{-1} in October 2006 and in May 2008, while the lowest values [160 g(C) m^{-2} month^{-1}] were recorded in December of both years.

The annual carbon uptake of the orchard was 13.45 t(C) ha^{-1} year^{-1} in the first observation period and 11.60 t(C) ha^{-1} year^{-1} in the second one (Fig. 8), possibly reflecting the dependency of the olive system on different meteorological conditions. In the first year, NEE was higher in each month in correspondence to higher air temperatures. The only exceptions were found in July and June of the second year, when no precipitation occurred. The peak of cumulative precipitation in November 2007 corresponded to a lower NEE and a higher ER.
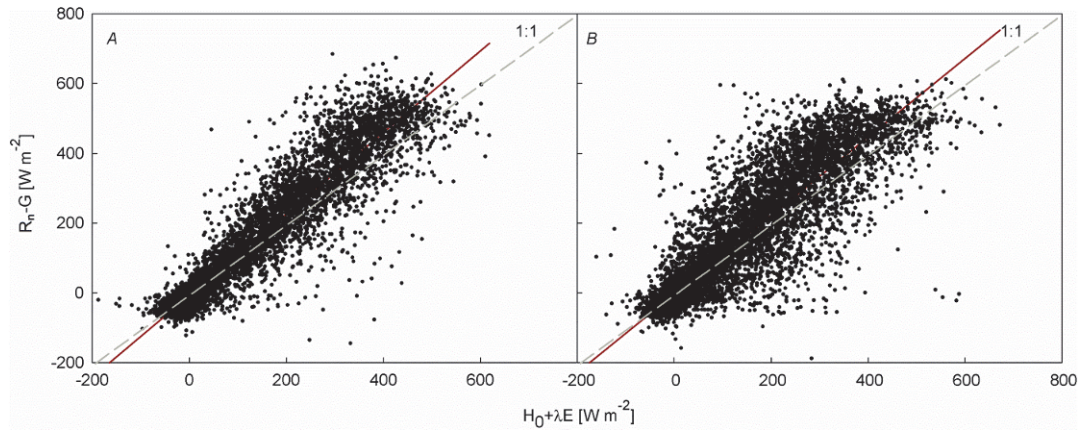

Fig. 5. Surface energy balance components and CO_2 flux (F_c) exchange during a typical summer day. H0 – sensible heat flux; LE – latent heat flux; R_n – net radiation; G – soil heat flux.

Fig. 6. Energy balance closure during two years of measurements. The linear regression (*solid line*) equation is $R_n - G = 1.17$ $(H_0 + \lambda E) - 8.04$ ($R^2 = 0.90$) for the first year (*A*) and $R_n - G = 1.12$ $(H_0 + \lambda E) - 4.02$ ($R^2 = 0.83$) for the second year (*B*). H_0 – sensible heat flux; λE – latent heat flux; R_n – net radiation; G – soil heat flux; $R2$ – square correlation coefficient.
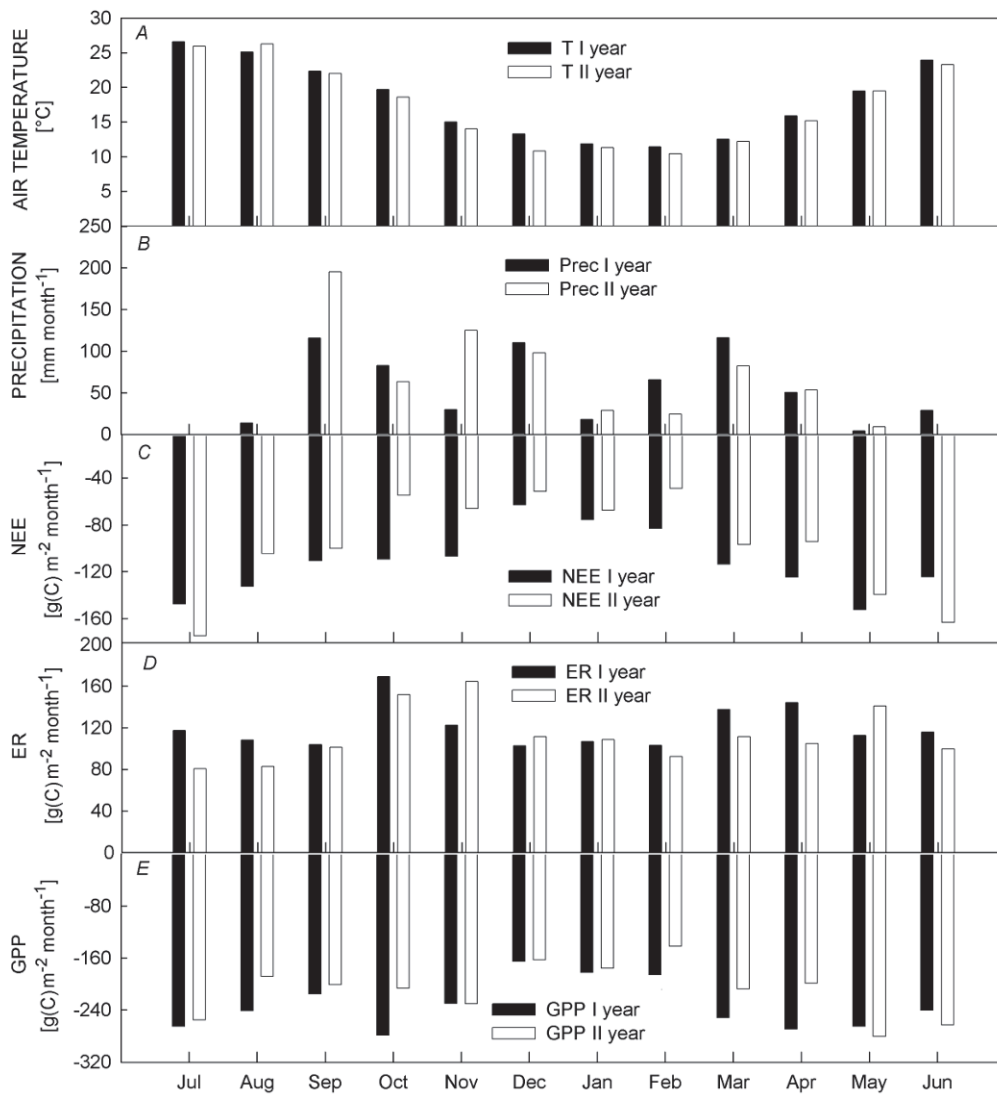

Fig. 7. Monthly trends during two years of measurement: (*A*) mean air temperature, (*B*) cumulated precipitation, (*C*) sum of net ecosystem exchange (NEE), (*D*) sum of ecosystem respiration (ER) and (*E*) sum of gross primary production (GPP).
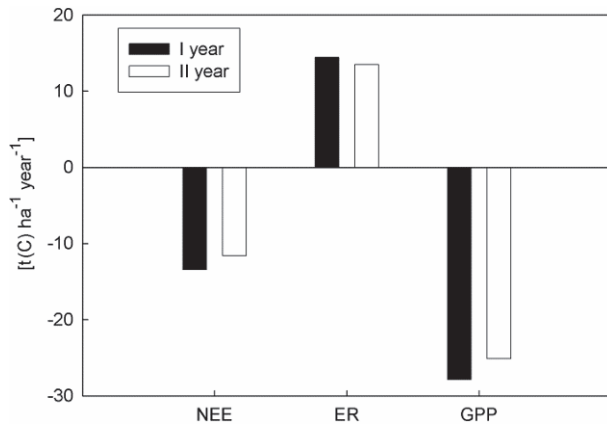
Fig. 8. Net ecosystem exchange (NEE), ecosystem respiration (ER) and gross primary production (GPP) in two years.
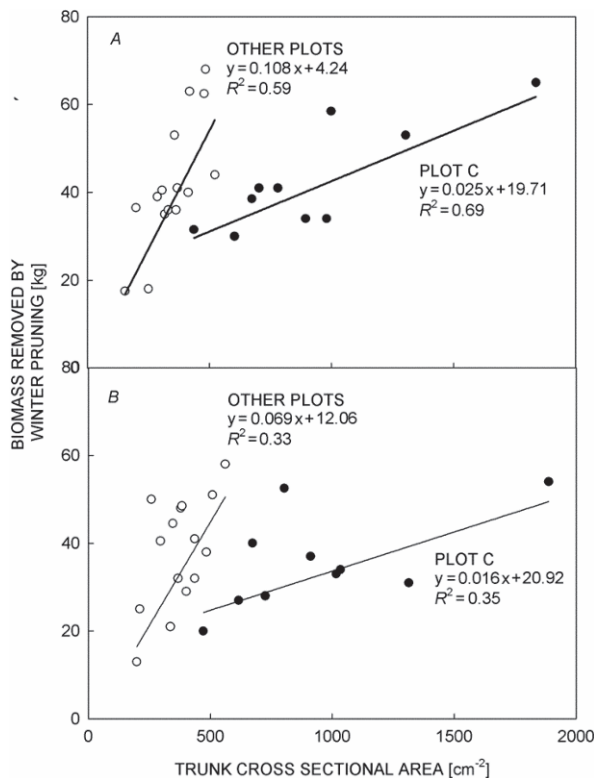

Fig. 9. The biomass removed by winter pruning *vs*. trunk cross sectional area as a function of the olive orchard age (*A*: first year; *B*: second year).

Biomass accumulation: Carbon concentrations in plant organs were calculated according to Grossman and DeJong (1994).

In Fig. 9, the biomass removed by winter pruning *vs*. trunk cross sectional area, as a function of the tree age, is reported for the two years. The regression lines obtained for older and younger trees were used to determine the amount of removed winter pruning material given, for each plot, the mean trunk cross sectional area.

The dry matter of the pruning material was (38.4 ± 8.2)% wood, (45.6 ± 5.6)% leaves and (16.0 ± 3.4)%
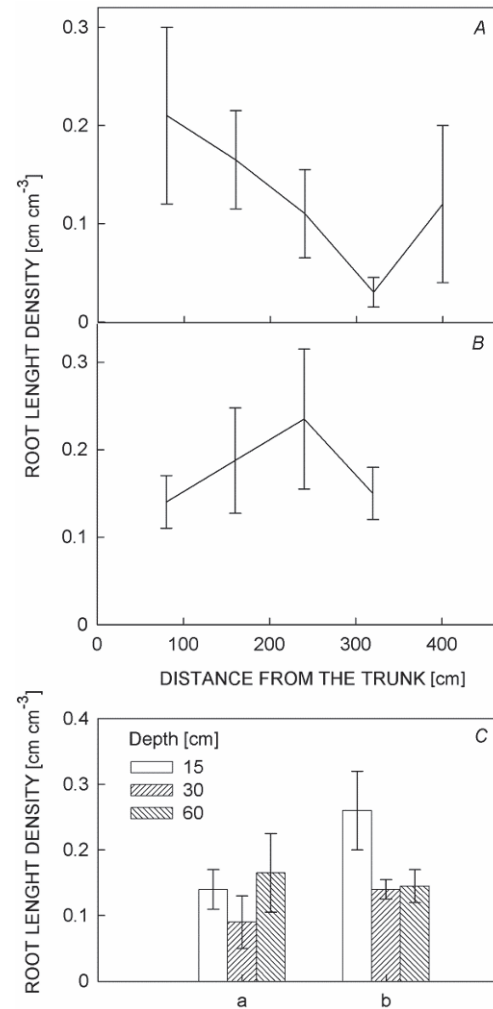

Fig. 10. Variation of the root length density (*A*) between rows (distance between the rows: 8 m), (*B*) between trees in the row (distance between trees in the row: 5 m); (*C*) variation of the root length density as a function of the sampling depth and position (a – between and b – along rows). $n = 3$.

shoots. In each component, the measured dry matter content was (62.3 ± 4.4)% in the wood, (52.3 ± 2.3)% in the leaves and (52.4 ± 1.8)% in the shoots. The carbon accumulated in the different canopy components was determined considering also natural leaf turnover, as leaves are normally renewed every 2 or 3 years (Villalobos *et al.* 2006).

In the analysis of the root density, a different root distribution as a function of the distance among trees was observed. Most of the orchard, namely all of the plots in which young plants were cultivated, was characterised by a rectangular tree spacing (Table 1). Because the intra-row distance was lower than the inter-row distance, the mean root length density reached a value of 0.18 ± 0.02 cm cm^{-3} within rows and 0.13 ± 0.02 cm cm^{-3} between rows. The order of magnitude of these values was the same as in Fernandez *et al.* (1991) and Dichio *et al.* (2002) in nonirrigated trees (0.177 cm cm^{-3} and

0.18 cm cm^{-3}, respectively). The variation of RLD as a function of the distance from the trunk can be observed in Fig. 10*A,B*. The lower value of RLD was observed at the midpoint between the rows: this can be explained by the higher distance between trees, which prevented roots from exploring the volume of soil located in the middle. The opposite was observed in the row, where the lower distance favoured a better root exploration between trees. The RLD also varied as a function of the sampling depth, reaching higher values at 15 and 60 cm irrespective of the position of sampling (Fig. 10*C*).

Root biomass for temperate and northern conifer and broadleaf forests has been estimated to be approximately 20–25% of the total aboveground biomass (Santantonio *et al.* 1977, Mac Dicken 1997, Li *et al.* 2003). For olive trees, Caruso *et al.* (2006) observed a similar canopy/root ratio (dry matter recorded 15 months after planting) on self rooted trees, and Sofo *et al.* (2005) reported for a young plantation a belowground biomass allocation of 27%.

In orchards and for evergreen species, Montanaro *et*

al. (2008) and Liguori *et al.* (2009) observed that annual C partitioned to the roots was 0.3 of the total fixed one.

According to these observations, we assumed that the annual carbon accumulated in the roots of both young and old trees was equal to 30% of the total accumulated by their aerial organs. The annual accumulation in above- and belowground components are summarised in Table 5. Very consistent values were found in two consecutive years. The annual covercrop was the main C storage pool, reaching for both years approximately 35% of the C accumulated, while oil contained approximately 10% and yield residues approximately 15%. Carbon allocated to canopy and trunk growth was slightly lower in percentage in the second year, when drier conditions occurred in the summer.

The total carbon accumulation in all components reached values of 12.2 and 11.5 t(C) ha^{-1} year^{-1} in the two years, respectively.

Discussion

The olive orchard considered in this study had the typical configuration of an intensive system, with 75% of its area covered by trees younger than 16 years. The concomitant presence in the same plantation of 25% of old plants (more than a century old) is frequent, due to the progressive conversion of traditional old grown systems to modern ones. The CO_2 fluxes quantified here were almost exclusively attributed to the young, intensive systems (250 trees/ha) as verified by the wind direction statistical analysis. A similar growth pattern distinguishing younger trees with respect to the oldest ones was also shown here by direct biomass accumulation measurements to verify the micrometeorological flux measurements in homogeneously aged trees. As reported for the same orchard by Pernice *et al.* (2009), evapotranspiration in cente

Table 5. Percentage of carbon accumulation in above- and belowground components for two years.

Component	Percentage [%]	
	Year I	Year II
Canopy growth	21.0	18.8
Husk (olive residues)	14.9	15.3
Olive oil production	9.5	10.0
Covercrop	34.2	36.1
Trunk growth	1.4	1.0
Root growth	14.9	14.5
Leaves turnover	4.1	4.3

nary trees is also lower than in younger ones, indicating different ecophysiological age dependent behaviour.

The NEE measured for such coverage during two years was 13.45 t(C) ha^{-1} year^{-1} and 11.60 t(C) ha^{-1} year^{-1}, with an average of approximately 12.5 t(C) ha^{-1} year^{-1}.

Such an amount of carbon fixed by the orchard was higher than that of many forests. Valentini *et al.* (2000) observed, in a series of ecosystems kept under observation by the Euroflux network, a significant positive correlation of carbon uptake with decreasing latitude: at 40° of latitude (about the same values as our orchard) the forest carbon accumulation is less than 6 t(C) ha^{-1} year^{-1}. The agricultural system examined here has to be considered very efficient from the physiological point of view, given the prevalent age of the trees (still in a very active growth phase) and the supply of irrigation to overcome the main water deficit limitation, avoid stomatal closure or trigger drought adaptation mechanisms (Connor 2005, Russeaux *et al.* 2008, Roussos *et al.* 2010). The continuous translucent trichome layer, which covers the abaxial surface of olive leaves, proved itself to increase reflectance in the thermal wavebands, which in turn is higher than transmittance at lower leaf water content (Baldini *et al.* 1997). Twelve year old plots showed a canopy land area projected on the ground equal to approximately 13 m^2, while in the 16 year old plot this value was even higher (almost 23 m^2). These data demonstrate the tendency of canopies to progressively cover the space between rows by the construction of new canopy structures as main and secondary branches. Light penetration within the canopy was optimised by the pruning, and LAI was within 3.

Environmental control on NEE (Law 2002, Yi *et al.* 2010) is also influential because temporal variations of meteorological variables reflected photosynthesis and ecosystem respiration. While carbon exchanges have been shown to be controlled by temperature at mid- to high latitudes, the most probable drivers in Mediterranean climates, where olive are produced, are radiation and

water, similar to subtropical and tropical areas (Nemani *et al.* 2003). A very high number of summer sunny days was, in fact, recorded in our site, with a high net radiation and PAR values.

The scarcity of information on the NEE of fruit tree orchards, olive included, does not allow a comparative analysis between the various species and orchard management techniques because of the different methodologies adopted (Almagro *et al.* 2010, Smith *et al.* 2010).

Here, a micrometeorological based approach was coupled with a biomass based inventorial method. The two independent approaches gave very similar results. The differences between the two records ranged between 9.3% and 0.9% in two years and they were easily explainable with intrinsic biases in the estimation of the aboveground:belowground biomass ratio and in the variability of applied winter pruning intensity among years.

Eddy covariance has now become a well tested technique, if carefully employed, to assess water and carbon exchanges from plant systems and it is able to give reliable information at the orchard scale and at variable temporal scales. Data obtained through this method complement small scale data at the leaf level for understanding the dynamics of the whole orchard as a soil-plant canopy-covercrop system. Ecophysiological traits related to orchard-atmosphere exchanges may be derived at the daily to monthly scale level, providing a dynamic overview within the seasonal growth patterns. On the contrary, the classic inventorial method, although

reliable, is applied only at a larger temporal scale and proves to constitute a sound control for the carbon storage values, as verified here.

The interannual and seasonal variability of the carbon balance terms has been already observed for forest ecosystems (Carrara *et al.* 2004). As occuring for leaf photosynthesis of the same species (Bongi *et al.* 1987), NEE showed a temporal dependency on air temperature, evidenced by the higher value (13.45 t C ha^{-1} year^{-1}) reached in the first year, when the mean annual temperature was 0.8 °C higher. Even if a fixed amount of additional water was provided through irrigation, the precipitation regime was also confirmed to be a carbon exchange driver in Mediterranean olive orchards. This evidence should be taken into account when addressing agrometeorological information to irrigation strategies (Perez-Lopez *et al.* 2007, Pernice *et al.* 2009, Rossi 2011).

The role of croplands in the European carbon budget and the potential for carbon sequestration studies are crucial because they can be included in the emission reduction targets (Smith 2004). The results reported here contribute to the assessment of the sink capacity of an important and largely expanding food crop. The relevant amount of NEE quantified is largely supporting the opportunity to couple LCA - calculated greenhouse gas emissions (Liu *et al.* 2010) with carbon uptakes in order to provide complete assessment of the environmental impacts of orchards.

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