Europ. J. Agronomy 63 (2015) 97–104

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Net ecosystem carbon balance of an apple orchard

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ARTICLE INFO

Article history:
Received 8 May 2014
Received in revised form
28 November 2014
Accepted 1 December 2014
Available online 11 December 2014

ABSTRACT

Fruit tree ecosystems represent an important land use type in Southern Europe. Nevertheless, limited information and large uncertainty currently exist about their potential role as a sink of atmospheric CO_2, which is measured through an index that accounts for all inputs and outputs of C, namely the net ecosystem carbon balance (NECB). In this paper, we studied the fluxes of C assimilation, the C release and the lateral C and their contribution to the NECB in an apple orchard at different time scales. Data of net ecosystem productivity (NEP) were recorded by eddy covariance and converted into ecosystem respiration and gross primary productivity (GPP). The net primary productivity (NPP) and the C partitioning among tree organs were also biometrically assessed. The study was carried out in the period 2009–2012 in a commercial apple orchard located in an intensive fruit production district of South Tyrol, Italy. We found a positive NEP from March to October and yearly NEP values of 403 $\mathrm{g\,C\,m^{-2}}$. GPP (1346 $\mathrm{g\,C\,m^{-2}\,year^{-1}}$ on average) was highest between May and September, when leaves intercepted the highest amount of PPFD. Tree growth accounted for more than 90% of the total new biomass produced in the orchard, the remaining part being represented by the herbaceous vegetation covering the orchard floor. Trees allocated to fruits approximately half of the yearly NPP, while they increased only to a limited extent their standing biomass. A significant fraction of NPP was also allocated to organs (leaves, pruned woody organs, etc.,) that feed the detritus cycle. The NECB was on average positive (69 $\mathrm{g\,C\,m^{-2}}$) but showed high variation among years, and in the year when fruit yields was very high (74 t fruits/ha), the NECB was even negative. NECB was accounted to a greater extent by the yearly increase of tree woody organs and to a minor extent by the C transfer to the soil from the decomposing litter. The most relevant agronomical suggestion of this study is that tree vegetative growth resulting into either increasing standing biomass and/or increasing tree litter should not be reduced if we aim at maintaining the CO_2 sink capacity of the apple orchard.

1. Introduction

The rising interest for carbon (C) budget at the global scale depends on the well documented effect of the increasing atmospheric carbon dioxide concentration on global temperature (IPCC, 2013). By sequestering significant amounts of C from the atmosphere, forests, and to a lesser extent, grasslands offer a strategy to mitigate global warming (Valentini et al., 2000; Smith et al., 2005; Luyssaert et al., 2007; Pan et al., 2011; Abdalla et al., 2013). In contrast, agricultural systems are often regarded as potential sources for atmospheric carbon dioxide (Smith et al., 2008; Ciais et al., 2010; Ceschia et al., 2010; Abdalla et al., 2013). However, perennial fruit plantations have intrinsic features that could contribute to maintain a long-term storage of carbon in the soil and a short- to medium-term storage in the wood. The eddy covariance approach has received large attention in the study of the C exchange between soil-vegetation and the atmosphere in forests, grasslands and other natural ecosystems (Baldocchi, 2008 http://www.fluxnet.ornl.gov/), but only limited information on woody agro-ecosystems is available (Testi et al., 2008; Zang et al., 2013; Zanotelli et al., 2013).

Apple (*Malus domestica*) is the most extensively cultivated deciduous fruit tree crop worldwide, with a surface of 4.8 million hectares, and a production of about 76 million tons (FAOSTAT, 2012). South Tyrol is one of the most intensive apple production areas with approximately 18.000 ha and average yields of nearly 1 million tons apples $\mathrm{year^{-1}}$. Intensively managed apple orchards have a potential for C sequestration due to: (i) an early bud burst

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http://dx.doi.org/10.1016/j.eja.2014.12.002

in spring and late leaf senescence in autumn, which promotes photosynthesis, (ii) an intrinsically high carbon assimilation rates, especially when trees bear a high number of fruits (Reyes et al., 2006), (iii) a relatively limited tree framework due to the widely used dwarfing rootstocks, which limits autotrophic respiration, and (iv) a widespread presence of a ground cover vegetation (Merwin, 2003) in the alleys between the tree rows, which is known to increase the soil organic carbon (Palese et al., 2014; Marquez et al., 2013). In some districts, such as where the present study was performed, apple represents the main agricultural crop in terms of economic value. An apple orchard lasts approximately 15–20 years and during this period it might perform as a source or as a sink for C, in the latter case by storing it in the woody organs, in the soil or on the soil surface.

The vegetation present in the orchard is responsible for a net flux of C entering the system through net photosynthesis that results in the gross primary production (GPP). Part of this carbon is used for the autotrophic respiratory processes (Ra) and the differences between GPP and Ra is equal to the net primary production (NPP). The heterotrophic organisms residing mainly in the orchard soil produce a net C loss (Rh). The sum of Ra and Rh gives the ecosystem respiration (R_{eco}). According to Buchmann and Schulze (1999), the net ecosystem productivity (NEP) is the amount of C resulting from the net ecosystem CO_2 exchange (NEE) being equal to GPP–R_{eco} or NPP–Rh. NEP (= –NEE) provides information on the ability of the ecosystem to sequester, if positive, or to release, if negative, C during the production cycle. Lateral C fluxes–represented by the harvested fruits, the addition of organic fertilizers or amendments, and by the trees removal at the end of the orchard productive cycle ultimately affect the ability of the ecosystem to store carbon in the soil and/or vegetation, defined as net ecosystem carbon balance (Chapin III et al., (2006)). The management of the apple orchard causes direct and indirect C emissions, which are accounted for in life cycle assessment (LCA) or C-footprint studies (Weidema et al., 2008), are not considered in this study.

This paper reports four-year data of C exchange monitoring at different time scales (daily, seasonal, and inter-annual) in an apple orchard located in the South Tyrol Province (Northern Italy), ultimately aiming to assess the NECB of this land use type.

More specifically, we addressed the following questions:

1) How assimilation, release, and lateral flows affect the net ecosystem carbon balance of the orchard at different time scales?

2) What is the relative contribution of the different NPP components to the NECB?

The achieved information will be placed within the frame of the sustainability of cultivation practices.

2. Material and methods

2.1. Experimental orchard

The study was conducted during the period 2009–2012 in a commercial apple orchard located in Northern Italy (Bolzano, Italy; 46°21′N, 11°16′E, 224 m above sea level). The trees, belonging to the variety Fuji, grafted on M9 rootstocks, were planted in 2000 at distances of 3 × 1 m. The orchard was managed following organic farming guidelines (Bioland-Südtirol; http://www.bioland.de/ueber-uns/landesverbaende/suedtirol.html). Soil management included periodic (up to three times a year) mechanical tillage of the top soil layer in a 1.2-m-large soil strip centered on the tree row, while a ground cover vegetation was present in the 1.8-m-large alleys (a mixture of grasses, legumes, and broad leaves herbaceous vegetation), which was mowed 3 times per year on average. Fertilization was carried out every year by distributing 500 kg ha^{-1} of the commercial formulate AgroBiosol® (Scheier Brennstoffe und Begrünungstechnik, Bürs, Austria) in the spring, and 400 kg ha^{-1} of the commercial formulate Azocor® 105 (Fomet S.p.A., S. Pietro di Morubio – Verona, Italy) in the fall. The loamy soil (USDA classification) had 0.17% total nitrogen, 2.46% organic matter, 1.43% organic carbon, and pH 7.4.

2.2. Continuous carbon dioxide exchange and meteorological measurements

The site was selected based on the favorable conditions for eddy-covariance (EC) measurement in terms of regular terrain and homogeneity of land surface cover (Zanotelli et al., 2013). An 8-meter tower was set up at the beginning of 2009 in an area surrounded by apple orchards for a minimum of 500 m in all directions. Eddy covariance measurements were carried out from March 2009 to the end of 2012 using a LiCor 7000 (Lincoln, NE, USA) CO_2/H_2O analyser and a Gill R3 (Gill Instrument, Lymington, UK) sonic anemometer located 4 m above the tree canopy. Data were collected and computed with Eddysoft software (Kolle and Rebmann, 2007). Low quality data for turbulence and stationarity were screened out according to the Foken and Wichura (1996) quality test. Gaps in data collection and flux values removed due to quality control concerns were filled with look-up tables (LUT) based on meteorological seasonal conditions. The observed data of NEE were used to assess GPP by extrapolating daytime R_{eco} values for a bimonthly period from the nocturnal LUT according to air temperature and soil humidity for the specific daytime half–hour period.

Solar radiation components were measured by CNR1 (Kipp & Zonen, Delft, Holland); air temperature by CS215 (Campbell Scientific Incorporated, Logan, Utah, United States; CSI hereafter), and soil water content by multiple TDRs (CS616, CSI). All meteorological data were logged by a CR3000 (CSI).

2.3. Vegetation measurements

An extensive survey was conducted during the dormant season of 2010 to assess the standing biomass of the apple orchard. Eleven trees differing in diameter were excavated to assess a specific allometric equation to correlate their above and belowground woody biomass with trunk circumference at 10 cm above the grafting point. Parameters and statistics of the allometric equations are reported in Zanotelli et al. (2013). Fine (<2 mm) and coarse (>2 mm) root distribution were assessed in the same period by an extensive soil core campaign (17 soil cores at different distances around apple trees, up to 60 cm depth and six replicates).

The annual growth was assessed for three years (2010–2012) in six plots (including 5 apple trees each) distributed within the orchard. Six biomass components were considered separately: leaves, fruits, aboveground woody tissues (which include trunk, branches, and shoots), belowground woody tissues (which include coarse roots and the belowground part of trunk), fine roots, and ground cover vegetation.

Monthly values of leaf and fruit number were taken starting from 2010 in one tree per plot. Nine branches, distributed at three different heights, were collected monthly from trees outside the selected plots, to establish the mean leaf and fruit dry mass by drying them in the oven at 65 °C until constant weight. The leaf area index (LAI, $m^2\ m^{-2}$) was calculated for three years (2010–2012) as following:

$$\mathrm{LAI} = \frac{L_{\mathrm{number}\times L_{\mathrm{area}}}}{T_{\mathrm{area}}} \tag{1}$$

where L_{number} is the number of leaves counted monthly in one tree per plot, L_{area} is the mean leaf surface determined once a month with the use of the LI-3000 + LI-3050 scanner (Li-Cor Lincoln, NE,

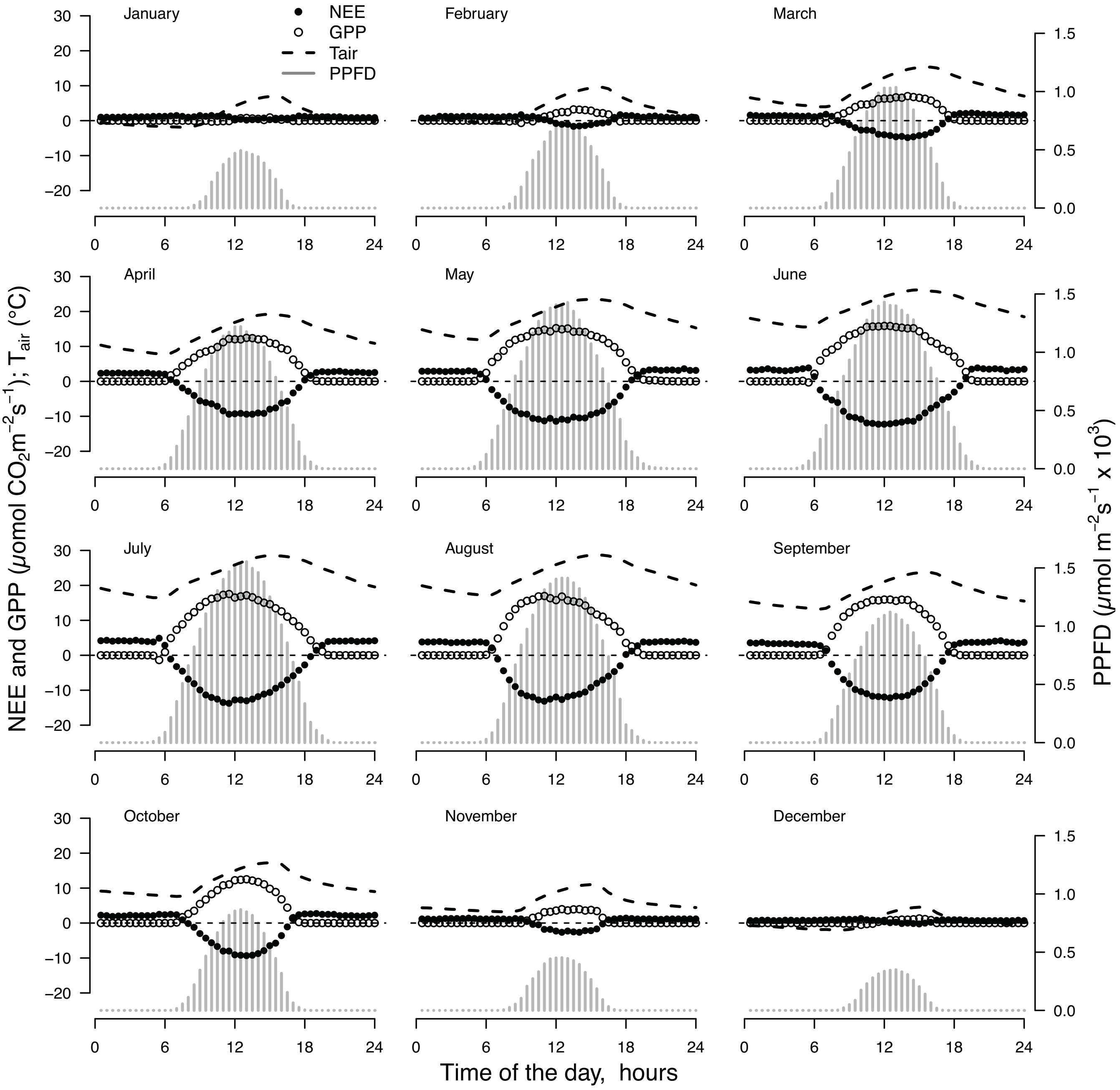

Fig. 1. – Average diurnal pattern of NEE, GPP (μmol CO_2 m^{-2} s^{-1}), Tair (°C), and PPFD (μmol m^{-2} s^{-1}) for every month of the year (average of 4 years).

USA) using all the leaves of the sampled branches, and T_{area} is the surface occupied by each apple tree (3 m^2). Dropped fruits were measured at harvest in each plot in 2010. In the present study were assumed to represent 5% of total fruit production. The trunk diameter at 10 cm above grafting point was measured monthly in each tree of the selected plots and allometric equations (see above) were applied to assess above and belowground woody biomass increase. Fine root growth was monitored by eight minirhizotrons installed at distances of 15, 35, 55, and 150 cm from the tree. They consisted of transparent Plexiglas tubes (8 cm diameter, 1 m length) inserted into the soil on an angle of 45° for approximately 90 cm, thus exploring a soil depth of 60 cm. Starting from 2010, root growth was monitored by collecting periodic images inside the minirhizotrons with a root scanner (CI-600 Root Scanner, CID-Inc Camas, WA, USA). To assess fine roots growth, we applied the image analysis technique, with the WinRHIZO software (Regent Instruments, Canada). The relative root growth rate was applied to the value of initial standing fine root biomass assessed by soil coring during the dormant season 2010. We assumed that all coarse root growth accounted for standing biomass increase, thus not contributing to the detritus cycle and that the ratio between coarse and fine roots was constant along the years. Ground cover biomass production in the alley was assessed by mowing the vegetation in an area of 1.8 m^2 close to each selected plot. The herbaceous biomass grown along the tree row in periods between tillage events was assumed to be negligible. Carbon content was assessed separately for each plant organ by elemental analyzer (FlashEA™ 1112, Thermo Fisher Scientific, Germany).

2.4. Data treatment and statistics

All the available half-hourly meteorological and C flux data over the four years were averaged on monthly basis to obtain an average daily pattern. The relative standard error of the mean was assessed on the daily cumulated values of the same dataset.

The net ecosystem carbon balance (NECB) was calculated as:

$$NECB = \mathrm{NEP} + \mathrm{OF} - \mathrm{FH} \tag{2}$$

where NEP represents the net ecosystem production (= −NEE), and OF (organic fertilizers), and FH (fruit harvest) are the lateral carbon fluxes occurring every year. Trees removal at the end of the productive cycle did not occur in the period 2009–2012 and thus it was not considered in Eq. (2). Fluxes of methane, carbon monoxide, volatile organic carbon, and dissolved organic and inorganic C were also not considered in the present study.

The carbon use efficiency (CUE) was calculated as:

$$\mathrm{CUE} = \frac{\mathrm{NPP}}{\mathrm{GPP}} \tag{3}$$

The harvest index (HI) was calculated as:

$$\mathrm{HI} = \frac{\mathrm{NPP}_{\mathrm{fruit}}}{\mathrm{NPP}_{\mathrm{total}}} \tag{4}$$

where $\mathrm{NPP}_{\mathrm{total}}$ was related only to apple trees.

The different components of NPP and the incoming external organic carbon were pooled together according to the common fate of the C: 1) C exported by the system with fruit harvest; 2) C stored in the system, i.e., the NECB; 3) C lost by heterotrophic respiration, calculated as the difference between (a) the sum of the NPP and lateral C inputs and (b) the sum of NECB, and exported C.

Descriptive statistic (average, standard deviation, and standard error) was used to characterize the average C fluxes and their uncertainties. All computations and plots were made with R statistical software (R Core Team, 2012).

3. Results

3.1. Eddy covariance measured carbon fluxes

The diurnal pattern of NEE in the twelve months (Fig. 1) clearly shows on a daily scale the seasonality characterizing a deciduous species growing in a temperate area of the Northern hemisphere, with negatives values (photosynthesis > respiration) distinctly occurring from March to October, being barely appreciable in February and November, and absent in January and December when the lowest temperature and radiation were recorded. The amounts of the daytime hours were reflected in the pattern of assimilatory C fluxes (Fig. 1).

The absolute highest instantaneous NEE and GPP (slightly higher than 15 μmol CO_2 m^{-2} s^{-1} and slightly less than 20 μmol, CO_2 m^{-2} s^{-1}, respectively) were measured between June and August (Fig. 1). In March, April, and October, the absolute values of GPP and NEE were higher in the afternoon (after 12:00) than in the morning. Morning and afternoon showed similar values of GPP and NEE in May June and September, while in July and August the largest values of GPP and NEE was recorded in the morning. The mean cumulated daily values of NEE, GPP, and R_{eco} (± s.e.) are given in Table 1: January and June were respectively the months with the highest and the lowest NEE (1.01 ± 0.04 and −3.00 ± 0.11 g C m^{-2} d^{-1}, respectively), while the highest daily values of GPP and R_{eco} are to be found in July (6.97 ± 0.09 and 4.15 ± 0.05, and g C m^{-2} d^{-1}, respectively).

Annual NEP averaged 403 ± 35 (s.e.) g C m^{-2} year^{-1}. The apple orchard acted as a sink for C (positive NEP) for a period ranging from 209 to 248 days per year. There was some variability among years with highest absolute values of NEE recorded in 2011 and minimum values recorded in 2009 (Fig. 2).

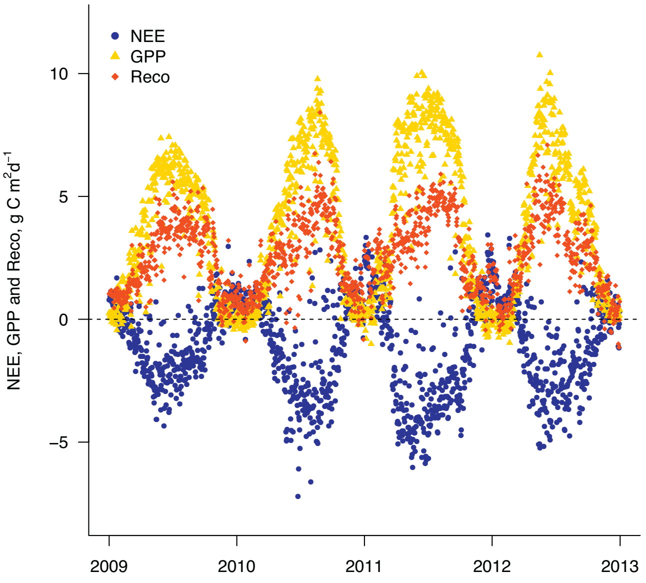

Fig. 2. – Daily values of NEE, GPP, and R_{eco} (g C m^{-2} d^{-1}) during the four monitored years (2009–12).

The average R_{eco} was 943 ± 36 g C m^{-2} year^{-1} increasing from February until July and decreasing thereafter (Table 1, Fig. 2). GPP averaged 1346 ± 52 g C m^{-2} year^{-1} but varied among years (Fig. 2) with the highest values recorded in 2011. GPP was negligible in January and December, linearly increased between February and May remained fairly stable between May and September, and decreased thereafter (Table 1).

3.2. LAI and NPP

The leaf area index (LAI) reached its peak between mid-June and mid-July (Fig. 3), with maximum (average ± s.e.) of 2.8 ± 0.11, 3.32 ± 0.20, and 2.77 ± 0.11 m^2 m^{-2} in 2010–12, respectively. In

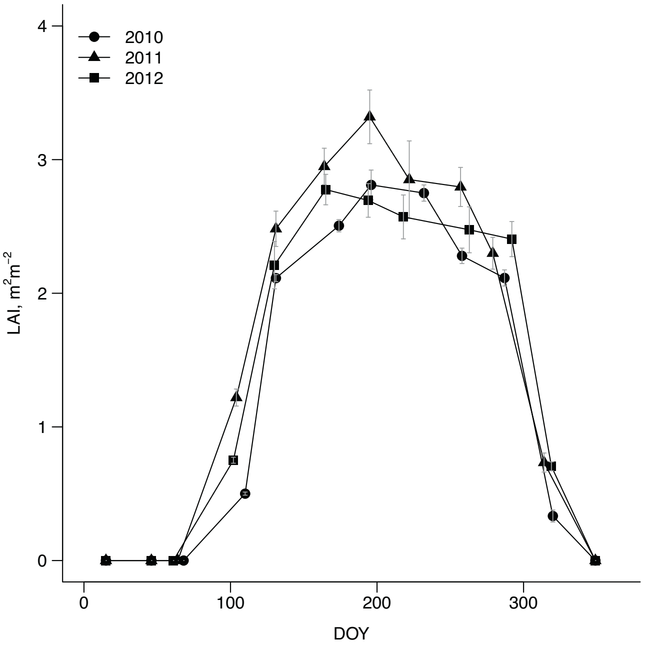

Fig. 3. – Leaf area index trend for the vegetative seasons 2010–12. Bars represent the standard error.

Table 1
– Quantification of the daily C fluxes (NEE, GPP, and R_{eco}, $g\,C\,m^{-2}\,d^{-1}$), the daily amount of photosynthetically active radiation (PPFD, $mol\,m^{-2}\,d^{-1}$), and the mean daily Temperature (Tair, °C) for every month of the year.

Month	NEE $g\,C\,m^{-2}\,d^{-1}$	GPP $g\,C\,m^{-2}\,d^{-1}$	R_{eco} $g\,C\,m^{-2}\,d^{-1}$	PPFD $mol\,m^{-2}\,d^{-1}$	Tair mean daily, °C
January	1.01 ± 0.04	0.09 ± 0.04	1.09 ± 0.03	9.07 ± 0.21	1.35 ± 0.42
February	0.65 ± 0.06	0.62 ± 0.06	1.26 ± 0.04	15.37 ± 0.32	3.32 ± 0.50
March	−0.26 ± 0.08	2.12 ± 0.08	1.86 ± 0.05	24.81 ± 0.44	9.20 ± 0.56
April	−1.75 ± 0.09	4.48 ± 0.10	2.73 ± 0.05	32.78 ± 0.53	13.37 ± 0.55
May	−2.90 ± 0.10	6.42 ± 0.11	3.51 ± 0.07	41.63 ± 0.61	17.91 ± 0.57
June	−3.00 ± 0.11	6.73 ± 0.11	3.73 ± 0.07	42.97 ± 0.68	21.08 ± 0.51
July	−2.83 ± 0.10	6.97 ± 0.09	4.15 ± 0.05	45.44 ± 0.54	22.62 ± 0.59
August	−2.43 ± 0.09	6.40 ± 0.10	3.97 ± 0.05	39.31 ± 0.50	22.80 ± 0.55
September	−1.82 ± 0.10	5.61 ± 0.09	3.79 ± 0.06	28.13 ± 0.48	17.94 ± 0.50
October	−0.89 ± 0.08	3.53 ± 0.08	2.64 ± 0.05	18.75 ± 0.35	11.39 ± 0.46
November	0.39 ± 0.05	0.91 ± 0.05	1.30 ± 0.04	8.87 ± 0.26	5.98 ± 0.36
December	0.69 ± 0.05	0.16 ± 0.04	0.86 ± 0.04	6.34 ± 0.19	0.40 ± 0.30

2011, the higher LAI values were likely the consequence of a light pruning performed in winter 2010–11.

Total NPP was 960 ± 70, 988 ± 71, and 768 ± 34 $g\,C\,m^{-2}\,year^{-1}$ in 2010–12, respectively. Fruit yield was 45, 74, 63, and 51 $t\,ha^{-1}$ (fresh weight) in 2009–12, respectively, with an HI ranging from 0.49 (2012) to 0.54 (2010).

On average, above-ground woody organs and leaves accounted for 23 and 12% of total NPP, respectively. Most of the C allocated to aboveground tree framework ($wood_{AG}$) was pruned and only part of it resulted into an increase of the standing biomass. Belowground C allocation to coarse ($wood_{BG}$) and fine roots accounted on average for 12% of total NPP, with the latter representing a sink approximately ten times bigger than coarse roots. The growth of the herbaceous vegetation present in the orchard alleys (groundcover vegetation) contributed to total NPP for less than 10% (Fig. 4). The carbon use efficiency was 0.71 in 2010, and 0.60 in 2011 and 2012, averaging 0.63 in the whole 2010–12 period.

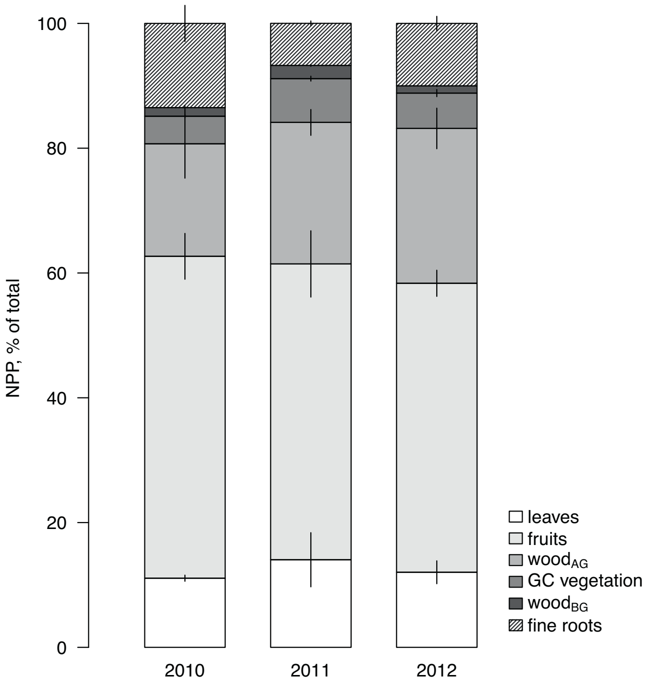

Fig. 4. – Contribution of the different NPP components (%) to total NPP in the three monitored years (2010–12). Bars represent standard error of the mean. $Wood_{AG}$ and $wood_{BG}$ means aboveground and belowground woody NPP, respectively. GC vegetation indicates the aboveground ground-cover vegetation production of the alley.

3.2. The fate of the organic carbon

The orchard started to perform as a net sink for C (positive NEP) every year between bud burst and full bloom in the spring, while in November, shortly after fruit harvest became a net source of C (Fig. 2 and Fig. 5). While the C entering the ecosystem via organic fertilizer represented a constant rate of 36 ± 1 $g\,C\,m^{-2}\,year^{-1}$, the amount of C in the harvested fruits markedly differed among years, therefore when fruit yield was 74 $t\,ha^{-1}$ (2010), NECB was slightly below zero (−55 ± 35 $g\,C\,m^{-2}\,year^{-1}$), while it was slightly positive in 2009, 2011, and 2012 (50 ± 32, 198 ± 44, and 82 ± 35 $g\,C\,m^{-2}\,year^{-1}$, respectively; Fig. 5). On average the NECB was positive for 69 ± 52 $g\,C\,m^{-2}\,year^{-1}$, resulting in a net carbon accumulation of 275 ± 74 $g\,C\,m^{-2}$ at the end of the fourth year (Fig. 5). Averaged across the studied period, most of C entering the orchard (942 ± 105 $g\,C\,m^{-2}\,year^{-1}$) derived from NPP (96%) while the remaining part was related to the organic fertilizer input.

By fruit harvest, 418 ± 62 $g\,C\,m^{-2}\,year^{-1}$ (44% of total input) were exported from the orchard. A significant fraction of NPP (dropped fruits, abscised leaves, pruned wood, mowed groundcover vegetation, and dead roots) as well as the organic fertilizer,

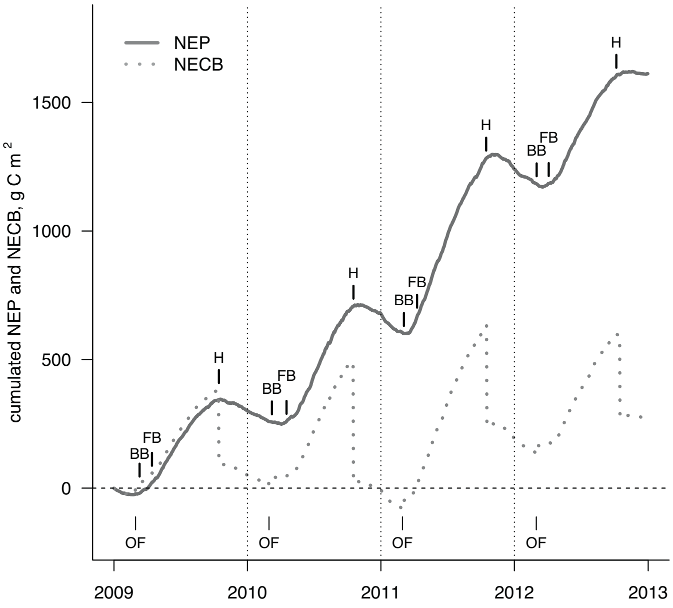

Fig. 5. – Cumulated trend of NEP and NECB ($g\,C\,m^{-2}$) during the four monitored years (2009–12). Letters above the NEP line indicate the occurrence of phenological phases (BB = Bud Burst; FB = Full Bloom; H = Fruit Harvest). Letters below NECB line indicate time of fertilization, which introduced organic carbon into the ecosystem (OF = Organic Fertilizer).

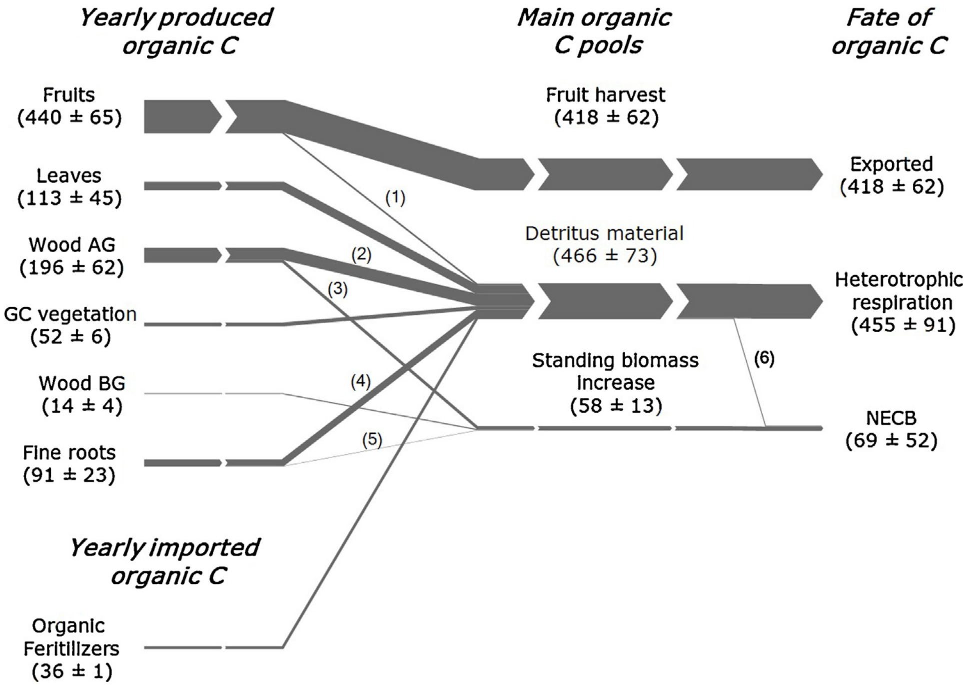

Fig. 6. – Overall scheme of the fate of the carbon made annually available by NPP and by organic fertilizer, with arrow size proportional to observed fluxes. Data are expressed in g C m^{-2} $year^{-1}$ and represent the average of three years (2010–12) and the standard error. On the left side the amount of carbon annually entering the ecosystem through photosynthesis fixation as net primary production (Wood AG and wood BG means aboveground and belowground woody NPP, respectively; GC vegetation indicates the aboveground ground-cover vegetation production of the alley) and through organic fertilization is presented. In the middle part of the scheme the main C pools formed during the vegetative season are shown. On the right side, the fate of the carbon is reported: the apple production is removed from the ecosystem at the end of the season (exported C); the heterotrophic respiration data are calculated by difference between the sum of the data on the left side of the scheme and the sum of NECB and exported C; the NECB represents the average net carbon balance during the measurement period. (1) refers to the dropped fruits (22 ± 3 g C m^{-2} $year^{-1}$); (2) refers to pruning material (167 ± 53 g C m^{-2} d^{-1}); (3) is the increment of above ground biomass (29 ± 9 g C m^{-2} d^{-1}); (4) fine root turnover (87 ± 28 g C m^{-2} d^{-1}); (5) is the increment of fine root standing biomass (5 ± 2 g C m^{-2} d^{-1}); (6) is the fraction of detritus material contributing to NECB (21 ± 53 g C m^{-2} d^{-1}).

became litter and fed the soil detritus cycle. The increment of the standing biomass derived from the sum of the above ground standing woody biomass (39 ± 12 g C m^{-2} $year^{-1}$), the below ground woody production (14 ± 4 g C m^{-2} $year^{-1}$) and the increment of fine root standing biomass (5 ± 2 g C m^{-2} $year^{-1}$). The NECB obtained by Eq. (2) (69 ± 52 g C m^{-2} $year^{-1}$) represented 7% of total C input and was mainly due to the increase in the standing biomass (58 ± 10 g C m^{-2} $year^{-1}$) while the difference (11 ± 54 g C m^{-2} $year^{-1}$), was attributed to a fraction not available for heterotrophic respiration of the detritus material (Fig. 6).

4. Discussion

4.1. Carbon exchange at different time scales

Several physiological studies have reported values of light-saturated leaf assimilation rates of single apple leaves along the season ranging from 6.9 to 18 μmol CO_2 m^{-2} s^{-1}; maximum values were recorded at 38 (Palmer et al., 1997) or at 120 days after full bloom (Wünche et al., 2005). Quantitative data about the carbon fixation potential in the apple orchard are however scarce and to our knowledge our study presents the most complete dataset of CO_2 exchange in apple orchards, as obtained in continuous for four consecutive years. Tree canopy gas exchange measurements using polyethylene chambers enclosing the whole tree crown (Corelli Grappadelli and Magnanini, 1993), have been carried out in apple only for limited periods; Giuliani et al. (1997), using the same system, reported maximum values of net photosynthetic rate (An) data between mid-August and mid-September of approximately 10 μmol CO_2 m^{-2} s^{-1}. In our study, the morning and afternoon fluxes contributed differentially to GPP and NEE according to the season (Fig. 1). In July and August, interestingly, the morning values of both GPP and NEE were markedly higher than those recorded in the afternoon. In the same months, Giuliani et al. (1997) found higher values of (An) in the morning, while in the afternoon the (An) values declined in the set of trees where the fruits were removed, a result that was explained by the authors with the low sink demand in that period of the year. In our study, however, the slight depression of C assimilation in the afternoon was recorded in highly-productive trees of a late-harvest variety where the fruits represented a strong sink also in summer, is more likely due to an excessive afternoon temperatures.

Auzmendi et al. (2013) scaled up C assimilation data from single apple leaf to tree level by considering canopy-intercepted PAR and the relationship between daily (An) and incident PAR in individual leaves; in their experiment, carried out during few days per month, the daily net photosynthetic rates averaged 7.2, 6.3, 3.0, and 3.3 mol CO_2 $tree^{-1}$ for July–October, respectively, which correspond to values of 13.4, 11.8, 5.6, and 6.1 g C m^{-2} d^{-1}, respectively. For the summer month, such values are markedly higher than those of GPP reported in Table 1, a fact that might be partially explained by considering the different PAR regimes of the two study sites (in July–August, >50 mol m^{-2} day^{-1} in Spain vs. 42 mol m^{-2} day^{-1} in our study) or may be caused by the applied upscaling modeling approach.

Only few papers have addressed the study of the C fluxes between soil-vegetation and the atmosphere in fruit trees through the eddy covariance technique. With the exception of Navarro et al. (2008), Testi et al. (2008), and Nardino et al. (2013), who reported C fluxes in a palm and in two olive plantation for two or more years, the literature on fruit tree refers to single year data or to short measurement campaigns (Rossi et al., 2007; Zhang et al., 2013; Zanotelli et al., 2013). In this study we have provided evidence of a significantly positive NEP of the apple orchard averaging 403 g C m^{-2}

year^{-1}. Based on data obtained in 2010 for the same experimental site, Zanotelli et al. (2013) stressed the fact that such values are slightly higher than temperate-humid deciduous forests as reported in the global forests database published by Luyssaert et al. (2007). The NEP data for the apple orchard are also significantly higher than average values (284 g C m^{-2} year^{-1}) of representative annual crop species cultivated in Europe (Ceschia et al., 2010), but lower than those typical of evergreen tree crops cultivated under Mediterranean climate. Nardino et al. (2013) reported annual NEP values for intensively managed olive orchard ranging from 1160 to 1350 g C m^{-2} year^{-1}. The difference between the two orchard types might be due to the larger carbon uptake period of olive plantations, which represented a sink for C all year round, opposed to the apple orchard, which showed a positive NEP for approximately eight months. Zhang et al. (2013) showed positive values of NEP in a *Pyrus bretschneideri* orchard in one of the most important fruit districts of China for approximately 6 months. The maximum daily values of NEP (in summer) between apple, pear (Zhang et al., 2013), and olive orchards (Nardino et al., 2013) are relatively similar and around 5 g C m^{-2} day^{-1}, while Testi et al. (2008) reported for olive a maximum daily values of NEP reaching 3.5 g C m^{-2} day^{-1}.

Under no limitations of temperature, water and nutrient availability, the seasonal variation of GPP values (Table 1) depends on the amount of photosynthetic active radiation (PPFD) intercepted by the leaves (Auzmendi et al., 2013). In our study, the maximum values of carbon assimilation occurred between May and August when approximately 60% of total yearly photosynthesis was measured. Both PPFD and LAI reached the maximum value in the June–August period when the average daily air temperature was 21.1–22.8 °C. The high GPP values obtained in May took place in spite of the fact that maximum LAI was not reached yet (Fig. 3), and are likely explained considering the optimal temperature (Fig. 1) for photosynthesis in that period (Greer, 2014; Ro et al., 2001).

4.2. Partitioning of NPP and NECB

By converting the NPP values into amounts of new biomass, we obtained values of 22.8, 23.4, and 18.2 t dry weight ha^{-1} in 2010–12, respectively, which are in line with those reported by Palmer et al. (2002) in New Zealand (upto 28 t ha^{-1}) and by Lakso (2011) in the USA (between 14 and 18 t ha^{-1}). Given the similar management systems applied, these small differences are likely due to the different growing season length and to environmental drivers like radiation and temperatures.

This study confirmed on a multiple-year scale the elevated values of CUE found for the same field site by Zanotelli et al. (2013) in 2010, and support their hypothesis that apple trees have relatively low respiratory costs, likely due to the high allocation of C assimilates to fruits and to the relatively low biomass in the tree framework.

Despite the uncertainties in the results due to the combination of different methodologies (Taylor, 1982; Richardson et al., 2008) and its high inter-annual variability, the NECB of the apple orchard after four years of monitoring indicates a net gain of C of 69 g C m^{-2} year^{-1}. In this respect the apple orchard differed from most of the annual crops cultivated in Europe, which, with the exception of rice, had a C export with yields higher than NEP (Ceschia et al., 2010).

The NECB was mainly accounted by a C storage in the above and belowground woody organs of the trees, and to a limited extent, by the input of carbon into the soil, deriving from the detritus material (Fig. 6). Several biological and human-driven processes affect the NECB of an apple orchard. This species has relatively high photosynthetic potential and obtains NPP and NEP values similar to an average temperate-humid deciduous forest (Zanotelli et al., 2013). The allocation of C among organs and its consequent fate at ecosystem level explain why NECB is only a relatively low fraction of NEP. In many apple production districts, the advancement in the management techniques allowed the achievement of steady yield close to 60 t ha^{-1} or even higher. This is the result of high partitioning of photosynthetic product to fruits, obtained at the expenses of the vegetative growth, which is depressed by a combination of techniques, including the use of dwarfing rootstocks and pruning.

In our study it clearly appears (Fig. 5) that if fruit yields are exceptionally high (i.e., as a result of unsufficient fruit thinning a high fruit set) as it happened in 2010, the NECB becomes negative and the orchard acts as a source of C to the atmosphere. From our data we could demonstrate only a limited contribution of the C entering the soil through the litter (see detritus material in Fig. 6) to the NECB. This C has a differential residence time in the soil depending on the initial chemical composition of the litter (Melillo et al., 1982, 1989; Tagliavini et al., 2007; Ventura et al., 2010) as well on the structure and on the initial C content of the soil (Stockmann et al., 2013). The increase of soil organic carbon is of interest for its role in mitigating CO$_2$ atmospheric level, and suitable orchard floor management strategies are under development to reach this goal without compromising the economical sustainability of the orchard (Neilsen et al., 2014).

5. Conclusions

From the evidences presented in this study it can be concluded that intensively managed apple orchards have a potential to act as sink for atmospheric C. Our study specifically suggests that the NECB could reach higher values if trees were allowed to produce a higher vegetative growth, and therefore a consequent higher C storage either in the tree framework and/or in the organs that feed the detritus cycle. Economic and ecological sustainability in fruit production should be reconciled, by allowing the trees to produce high but not excessive yields, which from one side would depress fruit quality, and on the other side, would adversely affect the vegetative growth. The adoption of more vigorous rootstocks and the elongation of the orchard life-span could at least be considered among the potential measures.

Considering that the C accumulation in the woody organs accounted for the majority of NECB during the mature phase of the trees and that the mean turnover time of highly productive orchards is about 15–20 years, it can be concluded that the C in the tree framework has a relatively low residence time. In this respect, it should be borne in mind that after tree removal, the woody structures can be also burned in home heating systems, thus substituting other energy sources, or processed to produce woody-chips, compost, or biochar (Ventura et al., 2014): both solutions increase the C residence time and should be taken into account as GHG mitigation practices (Smith et al., 2008).

Acknowledgments

This study was carried out with the financial support from the Provincia Autonoma di Bolzano/Bozen - Projects “Assessing the potential for CO$_2$ sequestration by apple orchards in South Tyrol”, “MONALISA – Monitoring key environmental parameters in the alpine environment involving science, technology and application”, from Minister of University–Prin 2008 Project prot. 2008LX3AYP_001 “Carbon fluxes in the apple orchard”, from “Assomela Soc. Coop.” and from the Free University of Bozen-Bolzano through internal projects to MT. The authors would like to thank Martin Thalheimer, George Wellington Bastos de Melo, Paulo Cassol, Christian Ceccon, Maddalena Bolognesi, Elisabetta Tomè and Silvia Folegot for their precious support throughout the study period.

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