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Net ecosystem carbon balance of an apple orchard

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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 $g\,C\,m^{-2}$. GPP (1346 $g\,C\,m^{-2}\,year^{-1}$ 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 $g\,C\,m^{-2}$) 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 year^{-1}. Intensively managed apple orchards have a potential for C sequestration due to: (i) an early bud burst

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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:

$$\mathrm{LAI} = \frac{L_{\mathrm{number}\times}L_{\mathrm{area}}}{T_{\mathrm{area}}} \qquad (1)$$

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,