Carbon sequestration in orchards and vineyards

Damiano Zanotelli[1]*, Nadia Vendrame[2]**, Álvaro López-Bernal[3]***, Giovanni Caruso[4,5]****

[1] *Faculty of Science and Technology, Free University of Bozen-Bolzano*

[2] *Department of Agronomy, Food, Natural resources, Animals and Environment, University of Padova*

[3] *Department of Agronomy, University of Córdoba, Córdoba, Spain*

[4] *Department of Agriculture Food and Environment, University of Pisa*

[5] *Center for Climate Change Impacts, University of Pisa*

Sequestro di carbonio in frutteti e vigneti

Riassunto. I sistemi arborei possono agire da accumulatori netti di CO_2 grazie alla loro capacità di stoccare carbonio organico nelle strutture permanenti e nel suolo. In questo articolo vengono esaminati tre importanti sistemi arborei da frutto quali melo, vite e olivo, che sono stati oggetto dell'"International Workshop on Carbon Sequestration in Horticultural Crops" tenutosi a Pisa il 30 ottobre 2018. La comprensione delle relazioni che intercorrono tra le variabili ambientali, i processi fisiologici e la gestione agronomica riveste un ruolo cruciale per una corretta stima dei flussi e dell'allocazione del carbonio in frutteti e vigneti.

Parole chiave: Melo, vite, olivo, flussi di CO_2, biomassa.

Introduction

The 2018 special IPCC summary for policymakers is likely the last of a long list of reports warning about the consequences of the continue rise of major greenhouse gases (GHGs) concentration in the atmosphere due to anthropogenic activity, with carbon dioxide that stably exceeded the threshold of 400 ppm (IPCC, 2018). There is increasing evidence around the globe on how the changing climate, caused by these unprecedented levels of GHGs, is impacting not only physical processes and biological systems (such as glaciers, permafrost, sea level, erosion, extreme weather events, marine and terrestrial ecosystems), but also human and managed ecosystem, with detri-

mental effects on food production, livelihoods, health and economics (IPCC, 2014). Terrestrial vegetation naturally subtracts CO_2 from the atmosphere storing it as biomass in its permanent structure or in the soil, thus representing a natural way to mitigate the atmospheric CO_2 increment (Buchmann and Schulze, 1999). The magnitude of the sink effect exerted by terrestrial ecosystems depends on the species composition, the geographical location and an ensemble of environmental variables and physical features that influence plant growth. For these reasons, different biomes may have substantially different capacity of storing carbon. A common scheme used to define the pathway of the carbon fluxes within an ecosystem is shown in figure 1. The intensity of carbon fluxes are conventionally expressed in μmoles CO_2 m^{-2} s^{-1} in the short time scale, while on a longer time scale (from days to year), they are integrated in unit of mass of C per unit of surface and time (e.g. g C m^{-2}y^{-1}).

The integral of the net CO_2 fixation rate by leaf photosynthesis is called gross primary productivity
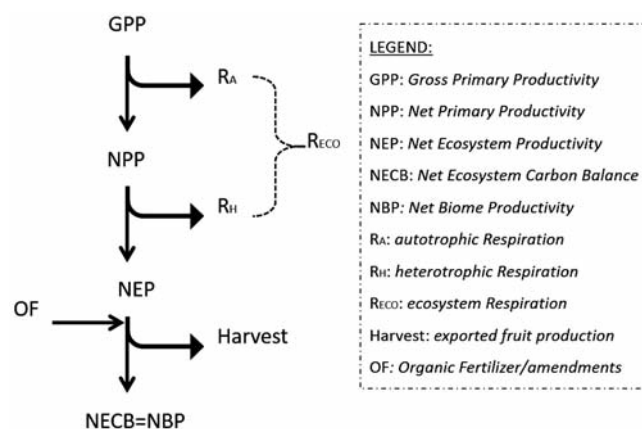

Fig. 1 - Carbon cycle of the agro-ecosystems (redrawn from Buchmann and Schulze, 1999).
Fig. 1 - Ciclo del carbonio negli agro-ecosistemi (ridisegnato da Buchmann and Schulze, 1999).

* damiano.zanotelli@unibz.it
** nadia.vendrame@unipd.it
*** alopez@ias.csic.es
**** giovanni.caruso@unipi.it

(GPP). Photo-assimilates resulting from the photosynthetic process can be used immediately to form new biomass in the different plant organs as a source of energy for all the living cells of the tree and are accumulated as starch. Processes using carbon to feed the existing organs or to stimulate new growth are known as maintenance and growth respiration, respectively, that cumulatively account for autotrophic respiration (Ra) (Amthor, 1989). The difference between GPP and Ra expresses the net gain of C by the plants, known as net primary production (NPP). This C accumulation can be seen as new biomass that appears into the vegetative and reproductive organs of vegetation, once the products of photosynthesis are allocated. A portion of NPP is not used for growth, but for the production of molecules that enter the atmosphere (volatile organic compounds) or the soil (root exudates) or are used by symbiotic microorganisms (e.g. mycorrhiza). The ratio between NPP and GPP indicates the efficiency of the ecosystem in using the fixed CO_2 to produce new biomass and it is known as carbon use efficiency (CUE).

Another important fraction of C returns to the atmosphere as CO_2 due to the respiration of heterotrophic organisms (Rh) living in the ecosystem and using the organic carbon as energy substrate. Autotrophic and heterotrophic respiration can be cumulated, representing the ecosystem respiration (Reco). The net balance between the inflow of C (GPP) and release by Reco is defined as net ecosystem productivity (NEP). In order to determine whether a system is storing or releasing CO_2 in the long run, one should also consider the so called "lateral" fluxes, which account for all the C released and removed from the system that is not related to biogenic activity (e.g. fire, wood or fruit harvest, loss of dissolved organic carbon) or that may enter the system due to management practices. By adding the positive and/or negative "lateral fluxes" to the NEP it is possible to determine the net ecosystems carbon budget (NECB) of the target system (also called net biome production, NBP, over larger spatial and temporal scales), which ultimately determines whether an agricultural system is acting as a sink or as a source of atmospheric CO_2 (Chapin *et al.*, 2006).

The micrometeorological technique of eddy covariance (fig. 2) allows to measure at very short time intervals the net ecosystem exchange (NEE = - NEP),

Fig. 2 - Examples of eddy covariance towers in fruit tree plantations: a) apple orchard (Caldaro - BZ); b) vineyard (Lison di Portogruaro - VE); and c) olive grove (Andria - BT).
Fig. 2 - Esempi di torri per la misura dei flussi ecosistemici di CO_2, H_2O ed energia tramite la tecnica micrometeorologica detta "eddy covariance", installate nelle tre coltivazioni arboree oggetto del presente articolo: a) meleto (Caldaro - BZ); b) vigneto (Lison di Portogruaro – VE); e c) olivo (Andria – BT).

resulting from the difference between the photosynthetic fixation and the respiratory losses of C (see following chapter). Several studies on carbon fluxes, based on the integration of eddy covariance measurements and other methodologies, have been published on scientific journals, mainly for unmanaged biomes (Luyssaert *et al.*, 2007; Schulze *et al.*, 2010; Valentini *et al.*, 2000). Given the share of the agricultural land, NEP and GPP have been also studied for field crop systems (Ceschia *et al.*, 2010; Ciais *et al.*, 2010; Smith *et al.*, 2010) and, more recently, for horticultural crops. Fruit trees, in particular, represent a significant portion of land use in several regions and have the potential to act as a net CO_2 sink, storing C in the permanent woody structure of the tree (Scandellari *et al.*, 2016) and in the soil, especially when soil management includes the presence of a grass cover (Chamizo *et al.*, 2017; Tezza *et al.*, 2019). Moreover, the possibility to use organic fertilizers or soil improvers (accounted as lateral fluxes in input) may enhances the capacity of fruit tree systems to act as a sink of CO_2.

Given the productive nature of agricultural systems, it is also important to consider the C emissions related to farming operations (expressed in CO_2 equivalents): such costs of machinery, fertilizers, irrigation, pest and weed controls, etc. They should be compared with biogenic NECB to provide a complete picture of the carbon footprint of the fruit production.

The International Workshop on Carbon Sequestration in Horticultural Crops, organized by the Italian Horticultural Society (SOI) held in Pisa in October 2018, aimed at giving an up-to-date overview about the CO_2 uptake and storing capability of major fruit tree crops, and this manuscript reports the findings on three main woody crops: apple, grapevine and olive.

Micrometeorological methods

The understanding and quantification of vegetation-atmosphere exchanges is a very active field of study, both for the very practical implications directly related to agricultural and forest productivity and for the more actual concerns related to climate change. The complexity of physical and physiological processes and feedbacks, linking the geosphere, biosphere and atmosphere, which are involved in the determination of fluxes makes this topic a great challenge for scientists of different research areas.

The transport of energy and matter in the lower atmosphere is mainly driven by turbulence, making fluxes particularly difficult to measure and model. Over the last century, several efforts have been made to increase knowledge on micrometeorology of plant canopies, starting from studies on surface energy balance (Bowen, 1926), flux-gradient theory (Dyer and Hicks, 1970), momentum exchange (Raupach and Thom, 1981; Shaw *et al.*, 1983; Thornthwaite and Holzman, 1939) and their combination (Thom, 1975). Today, micrometeorological methods allow for the most direct measurement of exchanges between a surface and the atmosphere, based on physical principles of fluid dynamics. In particular, the conservation equation describes the processes balancing the time rate of change of a scalar quantity at a fixed point in space. In ideal conditions, i.e. extensive, flat, and uniform terrain, and assuming no sources or sinks of the scalar in the layer of atmosphere between the surface and the measuring point, it can be shown that the turbulent flux measured at a certain height equals the diffusive flux at the surface (Baldocchi *et al.*, 1988). Based on this theoretical framework, net fluxes of different chemical atmospheric constituents (e.g. H_2O, CO_2, N_2O, and CH_4) can be measured at a known point above the surface without disturbing or altering the environmental conditions around the canopy. Another advantage of micrometeorological methods is that, even if measurements are carried out at a single point, the flux is representative of an upwind area (few hectares on average), thus being intrinsically spatially averaged.

In the past, to overcome the limit of inadequate instrumentation for the correct sampling of turbulent transport, exchanges between plants and atmosphere were measured applying methods based on flux-gradient relationships (Thom, 1975). This approach assumes that fluxes are directly proportional to the gradient of a quantity measured in the atmosphere above the canopy. However, in the 1980s, studies demonstrated the inconsistency of this simplistic assumption (Denmead and Bradley, 1987), showing the need to directly sample turbulent motion. This became possible in the 1990s, thanks to technological development of turbulence sensors and data logging systems. Today, eddy covariance (EC) is the most widely used method to characterize exchanges between vegetation and atmosphere (Baldocchi, 2014; Foken *et al.*, 2012). In a simplified context, fluxes can be considered one-dimensional and are determined as the covariance between the vertical wind velocity (w) and the quantity of interest (c) over a certain time interval (usually 30 min). The basic instrumentation of an EC tower consists of a 3D sonic anemometer and a gas analyzer. Sensors should be precise and fast enough to catch small variations of wind velocity and gas concentration at a sampling rate of at least 10 Hz, in

order to sample small-scale turbulence. Additionally, in order to sample the same volume of air, anemometer and analyser should be synchronized and placed as close as possible. Collected raw data need several corrections and quality control to fulfil theoretical assumptions before calculating final fluxes (Aubinet *et al.*, 2000). A good knowledge of atmospheric physics and programming skills would be required to properly manage instrumentation and implement the data processing. However, open-source software have recently become available [e.g. Eddy4R (Metzger *et al.*, 2017), EddyPro® (Li-Cor Biosciences)], extending the use of this method to researchers of other scientific areas. Indeed, EC is today commonly applied in several fields of research (e.g. ecology, agriculture, hydrology) to study ecosystem functioning in response to environmental drivers.

The robustness of instrumentation makes the EC technique especially suitable to perform long-term monitoring of vegetation-atmosphere exchanges. A coordinated effort to monitor fluxes at the global scale was established with the FLUXNET network (Baldocchi *et al.*, 2001), which greatly improved harmonisation of methodologies and data availability. More recently, long-term observation networks carrying out highly standardized measurements and processing of fluxes have been launched: the National Ecological Observatory Network (NEON) in the USA and the Integrated Carbon Observation System (ICOS) in Europe, with the aim to enable high quality research on climate change and increase usability of these data. Today, several time series of flux measurements of few decades are becoming available, allowing the study of ecosystem trends in response to climate change (e.g. increased atmospheric CO_2). These networks use advanced policies for data-sharing, effectively boosting a globally relevant monitoring effort (Dai *et al.*, 2018).

The EC method is a powerful tool to study the relations between ecosystem functioning and environmental drivers at different time scales, from minutes to decades. On the other hand, it requires flat, extended and homogeneous surfaces to collect reliable measurements, making not practically suitable the comparison of different managements in the same field, a feature very often desired by agronomists. The application of this technique on agricultural ecosystems, including woody crops, is still scarce compared to forests or other natural ecosystems. However, it can provide important information to improve the efficiency of management practices (e.g. irrigation, fertilization) to optimize plant performance and maximize yield. Additionally, studies on agricultural GHG

fluxes are essential to assess the role of this compartment in climate change and to identify sustainable management practices aimed at reducing the environmental impact of agriculture (fig. 2).

Apple orchard carbon budget

With 5.1 Mha of cultivated land, apple represents one of the main deciduous fruit tree crop worldwide (FAOSTAT, 2017). In Italy, 65% of apple production comes from the Trentino-South Tyrol region, where it represents the most relevant crop (ISTAT, 2017) and the entire sector is highly specialized. Modern apple orchards are planted at high tree densities (> 3000 trees ha^{-1}) with dwarfing rootstocks (i.e. M9) that limit the development of root systems. The aboveground part is normally trained as slender spindle to a height of 3 to 4 m. This unbalance between the above- and below-ground part of the tree makes it necessary the use of support structures such as cement poles and wires, to guarantee a stability and anchorage of the apple trees. The average fruit production of such systems is quite high, often greater than 60 tons ha^{-1}. Given the importance of the apple industry, especially at a regional scale, there is an increasing interest from the growers' associations as well as from the local authorities to know the magnitude of the carbon exchange of this crop, with the ultimate goal to understand whether it represents a net sink or a source of carbon for the atmosphere.

An eddy covariance tower was installed in an apple orchard located in the Valley of the Adige River (46°21'N, 11°16'E, 224 m above sea level, Municipality of Caldaro, Bolzano, Italy), an area intensively cultivated with apple. Since spring 2009, the carbon water and energy fluxes of the selected orchard (cv. Fuji grafted on M9 rootstock) were monitored continuously, and in this chapter we recall the major findings discovered so far.

The computation of the gross input of carbon entering the agro-ecosystem via photosynthesis (GPP ~1450 g C m^{-2} y^{-1}) showed comparable amounts between the orchard and the deciduous forests growing in similar temperate climatic condition (Luyssaert *et al.*, 2007). In non-managed ecosystems across many biomes, it is commonly thought by physiologists and modeleers, that plants respire a nearly constant fraction of approximately 50% of C absorbed by photosynthesis (Gifford, 2003; Piao *et al.*, 2010; Reich *et al.*, 2006; Vicca *et al.*, 2012). In the orchard, we found that autotrophic respiration was only approximately 30% of GPP (Zanotelli *et al.*, 2013). These findings indicate how the orchard have lower

maintenance requirements (relatively low Ra) with respect to un-managed ecosystems, which reflects a more efficient capacity to allocate photosynthates to biomass production (high carbon use efficiency, CUE). On the one hand, the optimal growing condition in terms of water and nutrient supply, radiation availability and temperature could explain this result, as it is known indeed that plants growing in fertile soils show higher CUE (Vicca *et al*., 2012). On the other hand, low maintenance costs observed in the orchard could depend on the high allocation of carbon products to organs having a relatively low nitrogen concentration and thus lower maintenance respiration (Reich *et al*., 2006), such as the fruits and the wood. Out of a total NPP of approximately 900-1000 g C m^{-2} y^{-1}, half of it was allocated to fruit production, while a ratio between 20 and 25% was allocated to permanent woody structure, mostly aboveground, 12% to leaves and 10% to fine roots. The rest, approximately 5% of total NPP, was the contribution of the grassed understory (Zanotelli *et al*., 2015), an allocation pattern measured also in other apple orchards (Palmer *et al*., 2002). The slightly higher amount of NPP found in this site (18-22 t dry matter ha^{-1}) with respect to other value reported in previous studies ranging from 13 to 18 t dry matter ha^{-1} (Palmer, 1988; Panzacchi *et al*., 2012), reflects the observed increasing trend of NPP with increasing orchard tree densities.

By averaging 7 years of cumulated measurements of net ecosystem exchange, the mean NEP of the apple orchard accounted for ~ 480 g C m^{-2} y^{-1}, while ecosystem respiration was ~ 950-1000 g C m^{-2} y^{-1}. Besides eddy covariance, the contribution of autotrophic and heterotrophic respiration on Reco was analyzed with the aid of a semi-automated multi-chamber system. Temperature, which is well known as the principal variable regulating the respiratory processes (Lloyd and Taylor, 1994), explained only approximately 50% of variability of both Ra and Rh, and it was demonstrated that also the photosynthetic activity significantly contributes to determine the magnitude of soil CO_2 efflux (Scandellari *et al*., 2015). The heterotrophic component represents a fraction between 65 and 77 % of total soil respiration (Panzacchi *et al*., 2012; Zanotelli *et al*., 2013) and approximately 60-65% of Reco. Refining the trenching technique used originally to separate Rh from root respiration, Tomè *et al*. (2016) demonstrated that approximately half the contribution of root respiration should be attributed to mycorrhizal fungi living in symbiosis with apple fine roots. Another important component of NPP, often neglected on account of inherent experimental difficulties, is root rhizodeposi-tion. By analyzing the C isotopic signature alteration of soil cores (taken from C4 plants fields) after one season of insertion in the soil, it was found that rhizodeposition can double the amount of below-ground NPP allocated to fine and coarse roots (Martinez *et al*., 2016).

To answer the main question of whether the apple orchards behave as a sink or source of atmospheric CO_2, we need to consider and quantify the lateral fluxes of C. If the average annual NEP of the apple orchard is very similar to that of a deciduous forest growing at similar latitudes, a significant part of it (85-90%) is removed by the system at harvest, when the fruits are exported for commercial purposes (fig. 3). Lateral input includes the practice to use organic fertilizers or amendments, which increase the carbon content of the system. When not exported as marketable fruits (~420 g cm^{-2} y^{-1}, 95% of C allocation to fruits), most of the new C stored in the system as biomass is going to feed the "detritus material" pool. Dropped fruits, abscised leaves, pruning material, fine root turnover, ground cover vegetation and organic fertilizers/amendments, thus becoming an energy source for heterotrophic organisms living in the soil of the orchards (Zanotelli *et al*., 2015). As reported in figure 3, a mature apple orchard over multiple years behaves as a net sink of CO_2, storing on average ~ 80 g C m^{-2} y^{-1}, equivalent to ~ 3 t CO_2 ha y^{-1}. Approx. 85% of NECB was attributed to an increase of tree standing biomass (woody structure and fine roots biomass), while some 10-15 g C m^{-2} y^{-1} increased the soil organic matter i.e a fraction of the detritus material not available for heterotrophic respiration. Considering that the majority of NECB is due to the C accumulation in the woody organs and that the mean turnover time of highly productive orchards is about 15-20 years, it is worth to understand its fate after tree removal, expanding the boundary of the analysis. In the area of the study, the woody structures of uprooted apple trees are normally 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 (Zanotelli *et al*., 2015).

On the pathway to sustainability, one way to provide indication about the environmental performance of fruit production is to calculate its carbon footprint, i.e. to assess the environmental "cost" of all the anthropogenic inputs needed for the specific economic activity, as global warming potential (GWP), expressed in CO_2 equivalents per kg of fruits (Lal, 2004).

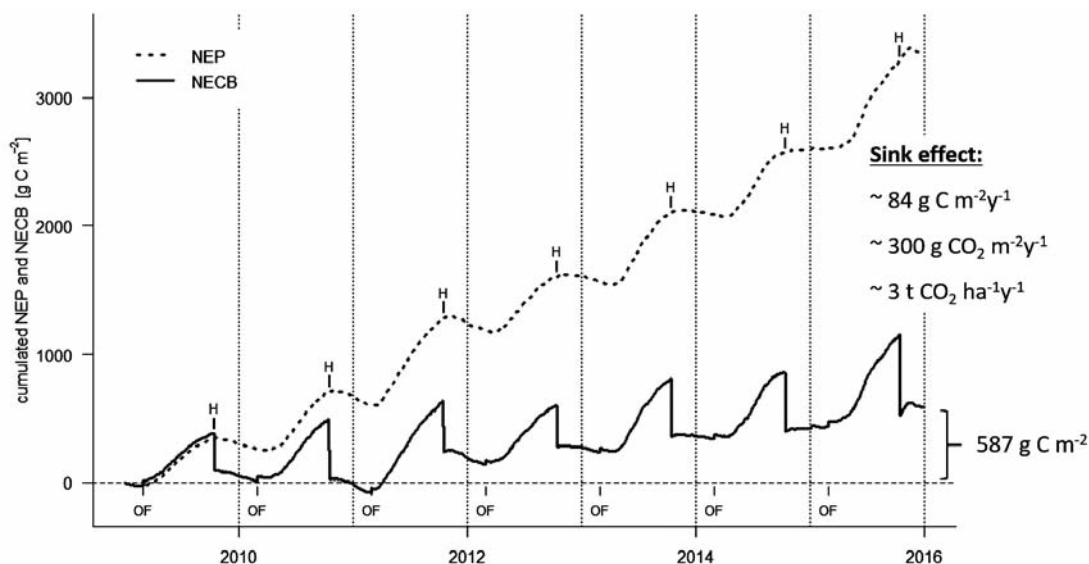Fig. 3 - Cumulated seasonal pattern of net ecosystem production (NEP) and net ecosystem carbon budget (NECB, g C m^{-2}) during seven years (2009-2015) of continuous carbon fluxes monitoring in the experimental apple orchard in Caldaro (BZ). The H letters above the NEP line indicate the occurrence of fruit harvest and the consequent export of C from the system. Letters below NECB line report the timing of fertilization, which introduces every year organic carbon into the ecosystem (OF= Organic Fertilizer). The sink effect was estimated dividing the cumulated NECB at the end of the monitoring season per the seven year of monitoring.
Fig. 3 - Andamento stagionale cumulato della produzione ecosistemica netta (NEP) e del bilancio ecosistemico netto di carbonio (NECB, g C m^{-2}) nei sette anni (2009-2015) di monitoraggio continuo dei flussi di carbonio nel meleto sperimentale di Caldaro (BZ). Le lettere H sopra la linea della NEP indicano le date della raccolta dei frutti e la conseguente asportazione di C dal sistema. Le lettere sotto la linea NECB riportano il momento della fertilizzazione, che introduce ogni anno carbonio organico nel sistema (OF, fertilizzante organico). L'effetto sink del meleto è stato stimato dividendo il carbonio accumulato alla fine del 2015 per i sette anni di di durata del monitoraggio.

Another index quite diffused in the horticultural sector is the primary energy use (PEU) expressed in MJ per kg of fruits or ha of surface (Zanotelli *et al.*, 2014). Several studies evaluated the environmental costs of apple production in different countries (Akdemir *et al.*, 2012; Blanke and Burdick, 2005; Cerutti *et al.*, 2011; Milà i Canals *et al.*, 2007; Mouron *et al.*, 2006; Page *et al.*, 2011; Pimentel, 2006; Reganold *et al.*, 2001). It is not easy to compare results coming from different studies due to the non-identical impact assessment methods and especially to the different assumption made by the authors in defining the boundary in time and space of their respective analysis. An important step forward to standardize the procedure for Life Cycle Assessment (LCA) analysis in the fruit sector was obtained by publishing the publicly available specification specific for horticultural products (British Standards Institution, 2012). The two carbon footprint estimates available for the apple production in the field (cradle to gate) of the area nearby the eddy covariance tower, indicates an emission between 0.04 and 0.06 kg CO_2 eq kg^{-1} of apple (Mazzetto *et al.*, 2012; Sessa *et al.*, 2014). This value includes the environmental costs of infrastructure, such as machinery, irrigation system and building, as well as those related to the annual management, such as fuel, fertilizers, pesticides, herbicides and labour. By dividing the positive NECB (~ 3 t CO_2 ha^{-1} y^{-1}) found experimentally (fig. 3), for the average fruit production (~ 60 t ha^{-1}), we obtain a net CO_2 uptake of approx. 0.05 kg CO_2 eq kg^{-1} of apple. We can thus assume that the apple production, in its first field phase, is a carbon neutral activity. By enlarging the analysis to the post-harvest phase, the carbon footprint of the apple increases, and it is strongly influenced by the type of packaging and the meaning and distance of the transport, ranging approximately from 0.15 to 0.40 kg CO_2 eq kg^{-1} (Boschiero *et al.*, 2019).

Vineyard carbon budget

Vineyards cover a surface of about 7.1 Mha globally (FAOSTAT, 2017), about 40% located in Mediterranean countries, with Italy alone representing 9% (OIV, 2018). Viticulture is also particularly important for the economic value of its final product. Indeed, the wine trade market is constantly increasing every year, and reached about 30 billion € in 2017 (OIV, 2018). A large part of wine producers have recently developed growing interest towards more sustainable wines, with the aim to demonstrate their consciousness of environmental issues and attract consumer support (Smart, 2010). Wineries can calculate the carbon footprint performing a LCA analysis of their products. This method have been adopted in

the wine sector, accounting for GHG emissions in each step of the production chain, but usually neglecting the biogenic carbon budget of the vineyard (Petti *et al*., 2015). This omission is primarily due to the complexity in vineyard carbon budget quantification and lack of common agreement on the methodology to apply (Arzoumanidis *et al*., 2013). Recently, the International Organisation of Vine and Wine (OIV) collected a list of methodological recommendations to account for GHG balance in the viticulture sector (OIV, 2017). Here, they specify that two different kinds of carbon storage should be taken into account: short-term for grapes and non-permanent vine growth, and long-term for above and below ground perennial biomass. Allometric relationships are indicated for the estimation of long-term carbon stored in vines; while short-term carbon sequestration is usually neglected due to lack of literature data and an approximation is often made considering the balance of storage and emissions in one year equal to zero. A precise quantification of vineyard carbon budget should be pursued as it has been showed that it can potentially contribute to offset CO_2 emissions caused by agronomic practices (Marras *et al*., 2015; Poeplau and Don, 2015).

Studies attempted to understand vine carbon allocation and sequestration capacity using destructive methods (Brunori *et al*., 2016; Scandellari *et al*., 2016). Additionally, vineyard carbon stocks have been estimated by upscaling plant allometric equations from vine level to field scale (Morandé *et al*., 2017) or by non-destructive measurements of vine structure with terrestrial laser-scanning technique (Keightley, 2011). These approaches can provide an assessment of vineyard carbon budget, but they have scarce spatial and temporal representativeness. Indeed, the number of sampled plants is usually limited, due to the large amount of manual work needed, and measurements are only representative of the status of the vineyard at the sampling time. These limitations can be overpassed with the application of micro-meteorological techniques (e.g. eddy covariance), allowing continuous and spatially-averaged measure-

ment of net CO_2 flux at the vineyard scale (see chapter 2). Only few studies have been conducted over vineyards in temperate climate, most of them reporting annual measurements (Gianelle *et al*., 2015; Marras *et al*., 2015; Pitacco and Meggio, 2015) and only one long-term study (3 years) (Vendrame *et al*., 2019). Results on the annual carbon budget of the vineyard are quite variable (tab. 1), ranging from 814 g C m^{-2} y^{-1} (Pitacco and Meggio, 2015) to 69 g C m^{-2} y^{-1} in the second year of measurements by Vendrame *et al*. (2019). This difference could be ascribed to vineyard characteristics (e.g. soil type, training system, vigour of the plants), management practices, and climate conditions. Even at the same site, the inter-annual variability of CO_2 fluxes was high, mainly due to environmental conditions, with climate extremes (e.g. heat waves) affecting the carbon sink capacity of the vineyard (Vendrame *et al*., 2019). Indeed, during period of water stress vineyard photosynthesis was depleted, showing a depression of CO_2 uptake in the central part of the day. Despite the high variability, all these studies demonstrated the ability of vineyards to act as carbon sink in the medium-to-long term.

The permanent biomass of grapevine is usually lower compared to other woody crops (e.g. olive groves, citrus orchards) (Scandellari *et al*., 2016), but it can still represent a significant carbon stock. Morandé *et al*. (2017) estimated the field carbon stock and partitioning of a 15-year old vineyard in California. From destructive sampling of several plants, they found that on average around 71% of vine carbon was stored in permanent structures (trunk, cordon and roots), 15% in fruits, and the remaining 14% in annual tissues (leaves and canes). The latter represents a significant amount, considering that it is built every year and in a relatively short period. After winter pruning, annual debris are usually left on the ground of vineyards, where they may accumulate as litter and increase soil organic carbon (Montanaro *et al*., 2017a). Indeed, the application of conservative management practices (e.g. retention of

Tab. 1 - Vineyard annual Net Ecosystem Productivity (NEP) measured with the eddy covariance technique at different sites.
Tab. 1 - Produttività Ecosistemica Netta (NEP) di diversi vigneti, misurata con la tecnica eddy covariance.

Site location	Cv.	Planting density (vines ha^{-1})	Annual NEP (gC m^{-2} y^{-1})	Reference
Negrisia di Ponte di Piave (TV)	Carmenère N.	3076	814	Pitacco and Meggio, 2015
South Sardinia	Vermentino	5952	195	Marras *et al*., 2015
Mezzolombardo (TN)	Teroldego Rotaliano	–	145	Gianelle *et al*., 2015
Lison di Portogruaro (VE)	Sauvingon Blanc	5050	207 69 127	Vendrame *et al*., 2019

pruning residues, no tillage, inter-row cover crops) has been shown to improve the carbon sink capacity of tree crops (Montanaro *et al.*, 2017b; Poeplau and Don, 2015). In particular, the use of cover crops in these peculiar agroecosystems is considered the most promising action to mitigate GHG emissions for Mediterranean agriculture (Pardo *et al.*, 2017).

Studies comparing the carbon content of tilled and cover-crop soils in vineyards, after 5-7 years of different treatment, confirmed that cover crops in the alleys can lead to an increase of carbon stock in the upper layers of soil (Agnelli *et al.*, 2014; Peregrina *et al.*, 2012; Smith *et al.*, 2008; Steenwerth and Belina, 2008; Wolff *et al.*, 2018). On shorter time scales, the effect of soil management can be assessed by direct measurement of CO_2 flux with soil chambers, which allow the study of soil exchanges with a temporal resolution varying from minutes to years. Few studies, measuring soil CO_2 fluxes before and after tillage in vineyards (Steenwerth *et al.*, 2016; Wolff *et al.*, 2018), reported an increase of CO_2 emission immediately after soil cultivation. However, this effect lasted for few hours/days and then fluxes returned to pre-tillage values. Recently, a study by Tezza *et al.* (2019) carried out long-term (almost two years) continuous measurements of net CO_2 fluxes at ground and ecosystem levels in a vineyard with grass-covered alleys. They highlighted the importance of a conservative soil management (no-tillage and inter-row herbaceous vegetation) in enhancing the carbon sink capacity of vineyards. Indeed, the net vineyard carbon uptake at the end of the study with conventional management (i.e. autumn soil ripping in the first year,

followed by tillage in autumn and spring of the second year) was 45% less compared to the no-cultivation scenario (fig. 4). Furthermore, on annual basis, the net carbon uptake by the grass-covered soil could have been about 55 g C m^{-2} y^{-1}, almost reaching the "4 per mille" goal of 60 g C m^{-2} y^{-1} necessary to compensate global anthropogenic carbon emissions (Minasny *et al.*, 2017). In this perspective, the cultivation of inter-row soil of vineyards, and woody crops in general, should be conveniently limited to increase their carbon storage.

In addition to carbon sequestration, a review by Garcia *et al.* (2018) reported several ecosystem services provided by the use of cover crops in vineyards: soil protection and biodiversity, water infiltration, weed control, pest and disease regulation, field trafficability. Despite these positive effects, cover crops are still rarely implemented in vineyards of Mediterranean regions because of fears of water and nitrogen scarcity due to competition. A significant reduction of nitrogen accumulation in the aerial part of vines has been reported (Celette *et al.*, 2009). As a consequence, vine vegetative growth is limited but, if the impact on yield is low, this could be considered positive to regulate excessive vine vigor in humid regions (Giese *et al.*, 2014). On the contrary, the competition for water between vine and cover crops is usually low (Steenwerth *et al.*, 2016) because of different morphology in root systems. Indeed, vine roots can explore greater depths (Archer and Strauss, 1985) compared to herbaceous vegetation, thus reducing the competition using water stored in deep layers unreachable by cover crops (Celette *et al.*, 2009; Klodd *et al.*, 2016; Wolff *et al.*, 2018). Additionally, the limited root system could cause rapid drying of herbaceous vegetation during summer drought spells, thus eliminating any competition with grapevine (Tezza *et al.*, 2019).

Olive orchard carbon budget

Olive orchards can be considered the most representative agricultural system in semiarid regions with Mediterranean climate, reaching 10.1 Mha worldwide in 2015 (FAOSTAT, 2017). In countries where the olive cultivation is extensive, such as Spain, Italy and Greece, olive orchards have become of high relevance not only from an economic perspective, but also from an ecological one. In this regard, olive orchards are perceived as powerful sinks of atmospheric CO_2 that could contribute to climate change mitigation due to their capacity to retain carbon in the permanent woody structures (i.e. branches, trunk and coarse roots) and the soil. However, scientific literature
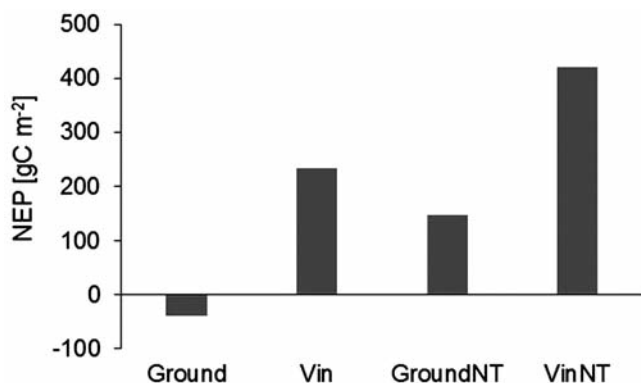

Fig. 4 - Total Net Ecosystem Productivity (NEP) from January 2015 to August 2016 of ground compartment (Ground) and whole vineyard (Vin) with conventional soil management and in the no-cultivation scenario (GroundNT and VinNT). Data derived from Tezza *et al.* (2019).
Fig. 4 - Produttività Ecosistemica Netta (NEP) totale da gennaio 2015 ad agosto 2016 del comparto suolo (Ground) e dell'intero vigneto (Vin) considerando una gestione del suolo convenzionale e una senza lavorazioni (GroundNT e VinNT). Dati derivati da Tezza et al. *(2019).*

assessing the carbon sequestration capacity of olive orchards is still scarce to some extent, and providing reliable numbers for it is still a challenging task.

One of the first experiment aiming at assessing the potential for carbon sequestration in olive trees was carried out by Sofo *et al.* (2005). Working in a young olive orchard in the Basilicata region (Italy), these authors measured the carbon accumulated in the different organs over the course of five years by destructively sampling some trees every winter. On average, the growth of permanent structures was calculated to be equivalent to the sequestration of 68.3 g C m^{-2} y^{-1} (2.5 t CO_2 ha^{-1} y^{-1}). Using a simple model based on the concept of radiation-use efficiency, Villalobos *et al.* (2006) estimated a higher value (191 g C m^{-2} y^{-1}) for intensive olive orchards in Southern Spain, although it was referred to mature trees capturing 50% of incident photosynthetically active radiation and growing under non-limiting conditions.

Obviously, the aforementioned pioneering determinations of carbon accumulation in permanent structures provide little information on the carbon exchange of the orchard as a whole, but a few more recent studies have used the eddy covariance technique for measuring CO_2 fluxes at the ecosystem scale (Brilli *et al.*, 2018, 2016; Chamizo *et al.*, 2017; López-Bernal *et al.*, 2015; Nardino *et al.*, 2013; Testi *et al.*, 2008). In general, all these works indicate that olive orchards tend to act as a sink of atmospheric CO_2, albeit there is a very large variability in measured NEE between them, sometimes even under similar environmental conditions. For instance, both Testi *et al.* (2008) and Chamizo *et al.* (2017) worked with irrigated olive orchards in Southern Spain where the soil was maintained weed-free. While the former obtained an NEP of 765 g C m^{-2} y^{-1}, the latter observed a value of 70 g C m^{-2} y^{-1}. Chamizo *et al.* (2017) ascribed their lower values, among other factors, to the different age of the plantations, as the mature trees (80 years old) of their experiment surely presented lower biomass production rates in comparison with the fast-growing young (< 6 years old) plantation of Testi *et al.* (2008). Besides, Chamizo *et al.* (2017) reports a NEP of 140 g C m^{-2} y^{-1} for an independent plot of the same olive orchard for which a weed cover was allowed to grow in the alleys from autumn to spring. The fact that NEP in the weed-cover plot was twice the one measured for the weed-free in that study might be explained by a positive effect of the cover on the soil carbon sequestration, as has been reported in other studies (Vicente-Vicente *et al.*, 2016).

The current body of literature further provides indication on the most important environmental and management factors modulating the different components of the carbon balance of olive orchards. The Gross Primary Productivity (GPP) is known to be a function of the intercepted radiation by the canopy, but it has also been demonstrated that it is strongly regulated by vapour pressure through the canopy conductance (Chamizo *et al.*, 2017; Testi *et al.*, 2008). Aboveground tree respiration has been found to vary during the season in response to three main factors (Pérez-Priego *et al.*, 2014): temperature, vegetative composition of the olive trees and the partitioning of assimilates between the different organs. In this regard, leaves and fruits are the main determinants of aboveground respiration, while the respiratory cost of the woody organs seems to be comparatively small. Similarly, belowground respiration is also thought to depend on the biomass of roots present and temperature, but the content of water and organic matter in the soil also seems to play a role. In this regard, Testi *et al.* (2008) found large differences in soil respiration rates between sampling points in the alleys and those located in the wet spots generated by the drippers, which highlights the difficulties that may arise when attempting to estimate belowground respiration rates at the orchard scale. To date, only the works by Almagro *et al.* (2009) in Murcia (Spain) and by Scandellari *et al.* (2016) in Tuscany (Italy) have estimated belowground respiration on an annual basis from the integration of discrete experimental measurements, with values being slightly over 820 g C m^{-2} y^{-1} in both cases.

Recent efforts in the modelling of olive orchards have led to the development of a complete olive growth and development model termed OliveCan (López-Bernal *et al.*, 2018) which, with a strong mechanistic basis, simulates the different components of the water and carbon balances. Briefly, OliveCan solves independently the water balance for two soil compartments representing the fractions of soil that are wetted or not by drippers (when irrigation is applied). For both soil compartments, the model uses several sub-models for the computation of infiltration and surface runoff (Romero *et al.*, 2007), drainage and evaporation (Bonachela *et al.*, 2001). Tree transpiration is estimated alongside gross assimilation from a soil-plant-atmosphere continuum sub-model (García-Tejera *et al.*, 2017) that takes into account soil water availability, root distribution, the interception of radiation and atmospheric CO_2. The partitioning of assimilates depends on phenology, which is the target of specific sub-models (De Melo-Abreu *et al.*, 2004). Maintenance respiration is computed for the different organs using algorithms derived from

Pérez-Priego *et al.* (2014) experimental data while growth respiration is deduced from assimilate partitioning and the composition of the growing organs (De Vries *et al.*, 1974). OliveCan does also simulates senescence of leaves and fine roots (López-Bernal *et al.*, 2018) and additional leaf shedding induced by frost damage (Barranco and Ruiz, 2005). Heterotrophic respiration is estimated with an adaptation of the model of Huang *et al.* (2009), which allows for closing the carbon balance at the orchard scale and simulating the dynamics of soil organic carbon. In relation to management, OliveCan simulates the impact of customizable operations of harvest, pruning, tillage and irrigation.

Given the quantity and detail-level of the processes simulated by OliveCan, this model represents a powerful research tool for assessing the ecophysiological and yield responses of olive orchards to different conditions of climate, soil and management with a wide range of practical applications. For example, in the context of the present paper, the model has great potential for analysing quantitatively the capacity of olive orchards to act as a sink of atmospheric CO_2 under different scenarios of climate and management. In the following, this is illustrated by showing the results of a dedicated case study.

Four virtual olive orchards with an initial age of 10 years were considered in the analysis. Planting densities were 400 trees ha-1 for two of them and 100 trees ha^{-1} for the others. For each planting density, two scenarios of water management were considered: rainfed and full-irrigation. Hence, the four virtual olive orchards were: high density irrigated (HDI), high density rainfed (HDR), low density irrigated (LDI) and low density rainfed (LDR). The simulations had a length of 50 years (1965-2014), using weather data from an agroclimatic station in Córdoba (Spain), with average values of rainfall and reference evapotranspiration of 580 and 1310 mm, respectively. A clay soil of 0.75 m depth was considered, with low initial organic matter. Initial values of ground cover were 35% for the high density orchards and 25% the low density ones. The harvest date was set on November 26th, irrespective of virtual orchard and season. Pruning was simulated every five years on the same date, with a fixed pruning intensity. In HDI and LDI, enough irrigation to match the maximum evapotranspiration was supplied daily from April to October.

Average annual values of GPP exceeded those of ecosystem respiration in the four virtual orchards, implying that they acted as a sink of CO_2 (tab. 2). Irrigation was found to have a strong influence on NEP, with HDI showing the highest average values

Tab. 2 - Annual averages ± standard deviations (n = 50) for different outputs of the model related to carbon exchange of the different simulated olive orchards. NEP is net ecosystem productivity, GPP is gross primary productivity, Reco is ecosystem respiration, RM is maintenance respiration, RG is growth respiration and RH is heterotrophic soil respiration. HDR: high-density rainfed orchard, HDI: high-density irrigated orchard, LDR: low-density rainfed orchard, LDI: low-density irrigated orchard.
Tab. 2 - Flussi di carbonio nelle differenti tipologie di oliveto prese in esame per la simulazione. I valori rappresentano i flussi annui cumulati + deviazione standard (N = 50). NEP, produttività netta ecosistemica; GPP, produttività primaria lorda; Reco, respirazione ecosistemica; RM, respirazione di mantenimento; RG, respirazione di accrescimento; RH, respirazione eterotrofica del suolo; HDR, oliveto ad alta densità in asciutto; HDI, oliveto ad alta densità irriguo; LDR, oliveto a bassa densità in asciutto; LDI, oliveto a bassa densità irriguo.

Orchard	HDR	HDI	LDR	LDI
NEP (g C m^{-2} y^{-1})	227 ± 5	366 ± 3	197 ± 5	257 ± 3
GPP (g C m^{-2} y^{-1})	904 ± 16	1322 ± 8	760 ± 11	940 ± 5
R$_{ECO}$ (g C m^{-2} y^{-1})	678 ± 11	956 ± 8	563 ± 8	683 ± 5
R$_M$ (g C m^{-2} y^{-1})	437 ± 8	579 ± 8	355 ± 5	413 ± 3
R$_G$ (g C m^{-1} yr^{-1})	191 ± 5	317 ± 3	167 ± 3	224 ± 3
R$_H$ (g C m^{-1} yr^{-1})	49 ± 2	63 ± 2	38 ± 2	46 ± 2

followed by LDI, HDR and LDR. The irrigated orchards also presented lower inter-annual variability in NEP, GPP and Reco than their rainfed pairs. Simulated annual NEP values were below those estimated by Testi *et al.* (2008) and above those obtained by Chamizo *et al.* (2017), irrespective of the olive orchard. The cumulative 50-year NEP ranged from 668 t CO_2 ha^{-1} in HDI to 361 t CO_2 ha^{-1} in LDR, resulting in an average annual NEP of 197 g C m^{-2} y^{-1}. With regard to the components of Reco, maintenance respiration (RM) was responsible of the most significant CO_2 efflux (on average, 62 % of Reco), followed by growth respiration (RG, 31 %) and heterotrophic soil respiration (Rh, 7 %), with slight variations between the four orchards (tab. 2).

Figure 5 provides insight into the seasonal dynamics of GPP, Reco and NEP for the four simulated orchards. Regardless of the case, the average monthly Reco was low during winter and increased as the season progressed, reaching a maximum by July. Subsequently, Reco decreased progressively until winter. The average monthly GPP mimicked such pattern, although the rainfed orchards (i.e. HDR and LDR), exhibited the maximum values by June instead of July (fig. 5A and 5C) due to the effect of water deficits on stomatal conductance and hence photosynthesis. Apart from this, the four orchards differed in the absolute values of both GPP and Reco. The highest and lowest monthly GPP and Reco were always found for HDI and LDR, respectively, with HDR and LDI showing intermediate values. NEP
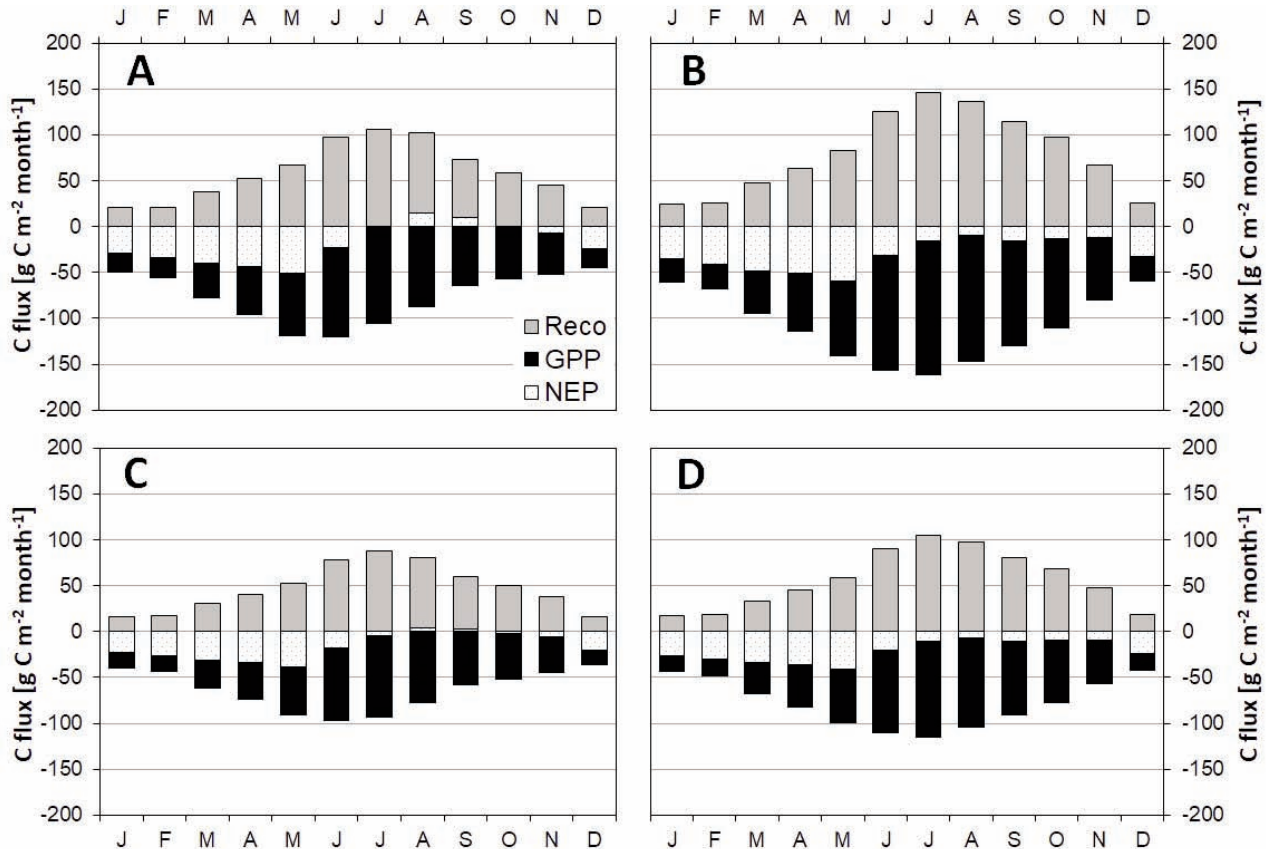
Fig. 5 - Monthly values of gross primary productivity (GPP), ecosystem respiration (Reco) and their difference, the net ecosystem productivity (NEP), for the high density rainfed (HDR, A), high density irrigated (HDI, B), low density rainfed (LDR, C) and low density irrigated (LDI, D) simulated olive orchards. Values are averages of 50 years.
Fig. 5 - Valori mensili di produttività primaria lorda (GPP), respirazione ecosistemica (Reco) e produttività netta ecosistemica (NEP) per gli oliveti ad alta densità in asciutto (HDR, A), ad alta densità irrigui (HDI, B), a bassa densità in asciutto (LDR, C) e a bassa densità irrigui (LDI, D) presi in esame per la simulazione. I valori sono medie di 50 anni.

dynamics revealed a progressive increase from winter to spring, reaching a maximum by May. Up to this point, the high density orchards presented higher NEP rates than the low density ones, with slightly similar values for irrigated and rainfed orchards. Following May, monthly NEP decreased sharply and low values were observed until December. During this period, differences in NEP seemed to be more related to water supply than to planting density, as HDI and LDI generally maintained higher values than HDR and LDR. Furthermore, HDR and LDR occasionally yielded slightly positive monthly NEP rates from late summer to early autumn (fig. 5A and 5C), which indicate that there are transitory periods for which the orchards acted as a source of CO_2. In the simulations of the HDI orchard, an average of 115 g C m^{-2} y^{-1} was incorporated into permanent aboveground biomass, which is within the range defined by aforementioned estimates by Sofo *et al*. (2005) and Villalobos *et al*. (2006) for orchards of similar characteristics. As a final remark, the positive effect of irrigation on NEP observed in this case study highlights once again that

the orchard management can have a strong impact on the carbon balance of olive orchards.

Conclusions

In the recent years, a growing body of literature assessing the carbon fluxes of woody horticultural crops has been published, partially filling the gap of knowledge regarding the role that these agro-ecosystems play in regard to atmospheric CO_2 sequestration. Taking advantage of the outcomes of the "International Workshop on Carbon Sequestration in Horticultural Crops", held in Pisa on the 30th of October 2018, we reviewed the state of the art of three fruit tree species: apple, grapevine and the olive trees. Experimental data, primarily obtained thanks to the application of micrometeorological methods such as eddy covariance, allowed to quantify the net carbon exchange of these ecosystems for several years and in different environmental and management conditions, as well as to assess the different components of their C cycle. Besides a marked inter-annual varia-

bility reported for each tree crop, their yearly cumulated NEP showed similar amounts, and comparable with un-managed systems. Orchard management plays a pivotal role in determining the amount of C fluxes, possibly allowing, to some extent, a control of the C storage capacity of these systems. The following practices can be listed as the most influential:

- Increasing plant density have been demonstrated to increase NPP and NEP in both the apple and the olive orchards.
- Using conservative tillage and cover crops also increased NEP in vineyards and olive orchards.
- The application of organic fertilizers and soil improvers are responsible to introduce carbon in the systems and likely to increase soil organic matter content.

More generally, providing good conditions for plant growth contributes to increase the C sequestration capacity. This was particularly relevant when comparing irrigated versus rainfed olive groves, with the former showing sensibly higher C fluxes and storing capacity.

Most of the aforementioned management practices that increase the C storing capacity of the orchards, have also a beneficial effect on ecosystem services, such as increasing the biodiversity, the soil water retention, the soil organic matter and the overall resilience of the agro-ecosystems (Demestihas *et al.*, 2017; Poeplau and Don, 2015; Turrini *et al.*, 2017).

NECB is the index that finally tells whether a system is storing or releasing C on an annual basis. Although published results for fruit trees are still scarce, evidence of a positive NECB (i.e. net sink) has been reported over multiple years for an intensive apple orchard, while the large variety of growing conditions produced contrasting results in olive groves and possibly in grapevine. Based on these outcomes, it appears clear the need for the horticultural sector to move toward an ecological intensification, where the necessity to keep high fruit production targets in terms of quantity and quality, is coupled with the adoption of management practices that can improve carbon storage and minimize negative impacts on the environment. Keeping high yield standards is not only important for fruit growers, but it will also decrease the fruit C footprint.

The carbon budget of an ecosystem is highly dependent on environmental conditions affecting physiological processes, and this intrinsic variability is higher in the case of agroecosystems due to site-specific management practices. Thus, long-term studies of CO_2 exchanges at different sites are fundamental to assess the role of woody crops in the global CO_2 budget, aiming at the development of general relations between climate and carbon sequestration. In particular, experimental data coupled with models, such as OliveCan, possibly adapted to the different fruit tree species, represent a powerful tool to generate different scenarios and predict the consequences in C assimilation, allocation and storage capacity of the agro-ecosystems under changing growing conditions. This information can be used to address agricultural and environmental policies towards more sustainable agriculture.

Abstract

Climate change, caused by unprecedented concentrations reached in the atmosphere by major greenhouse gases, is responsible for detrimental effects also on agricultural ecosystems. Woody tree crops, representing significant portions of land surface in many regions, have intrinsic features that allow them to potentially act as net CO_2 sink, storing it as organic carbon in their permanent structure and in the soil. Taking advantage of the outcomes of the "International Workshop on Carbon Sequestration in Horticultural Crops", organized by the Italian Horticultural Society (SOI) and held in Pisa on the 30th of October 2018, this paper reviews the major findings in the assessment of carbon fluxes in three fruit tree systems: vineyards, apple and olive orchards. In general, the gross primary productivities (GPP) of the examined woody agroecosystems are comparable with those of temperate forests, with higher efficiency in allocating the synthesized carbon in new biomass, possibly due to lower growth and maintenance costs. However, the carbon storing capacity is highly variable in time and space and it is strongly dependent on climatic conditions and orchard management. The major factors influencing orchards net ecosystem production (NEP) includes the seasonal environmental conditions, planting density, irrigation and soil management, with water supply and cover crops producing positive ecosystems services not limited to carbon sequestration. The orchard net ecosystem carbon budget (NECB) is determined by considering the lateral carbon fluxes, with the harvesting of fruits and the use of organic fertilizers and soil improvers representing the most influential practices. In general, higher carbon storage capacity of fruit tree systems is possible through an intensification of ecological practices, adopting strategies that aims at minimizing negative environmental effects such as nutrient leaching, soil erosion, loss of biodiversity, while maintaining high yield performance.

Understanding the relationships between physiological processes and specific management practices and environmental variables, either via long term monitoring experiments and/or the calibration of specific models, is crucial to get a clearer picture of the carbon fluxes occurring in changing growing conditions, and to predict the response of the orchard under different scenarios.

Keywords: Apple, grapevine, olive, CO_2 fluxes, biomass

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