

Study of the Carbon Budget of a Temperate-Climate Vineyard: Inter-Annual Variability of CO₂ Fluxes

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Abstract:

Agriculture can play a positive role in the global carbon budget through reduction of emissions and increase of soil carbon sequestration. Woody crops, like vineyards, present biological, structural and management peculiarities (e.g. perennial structure, abundant pruning debris, inter-row cover cropping), which allow to potentially sequester a significant amount of CO₂. However, only few studies have been conducted over this kind of ecosystems. In this paper, we present results from a long-term study running in North Eastern Italy on the carbon budget of a vineyard (cv *Sauvignon Blanc*, Guyot pruned, VSP trellised, with grass-covered alleys). We used the eddy covariance technique to continuously monitor the

net ecosystem CO₂ exchange (NEE), and here we analyze the first three years of measurements (May 2014 to April 2017). The vineyard showed to act as a moderate carbon sink, with an average annual net carbon uptake of 134 gC/m². However, the inter-annual variability of NEE was considerably high and environmental conditions during vine growing season showed to have a strong impact. The summer of 2014 was characterized by plenty of rainfall and the annual carbon uptake was the highest (207 gC/m²). On the contrary, in 2015, several heat waves reached the area and the annual carbon uptake decreased to 69 gC/m². Elevated air temperature and low soil moisture in summer significantly reduced net carbon flux in the period of the year when the activity of the vineyard is at its maximum. Nevertheless, we showed that the vineyard can behave as carbon sink on the medium-long term, and we suggest this should be taken into account in agricultural and environmental policies, complementing standard Life Cycle Assessment of the wine production chain.

Key words: Vineyard, carbon sequestration, gas exchange, environmental sustainability.

Introduction

Successful crop cultivation is tightly connected to the correct management of its carbon budget. More or less directly, consciously or effectively, in fact, growers control carbon fluxes and stocks to optimize overall plant performance and maximize yield. In this respect, cultivation of woody perennials shows important specificities, because of their peculiar biology and common management techniques, which allow them to potentially sequester more CO₂ from the atmosphere (Gianelle et al. 2015, Scandellari et al. 2016, Vicente-Vicente et al. 2016, Zanutelli et al. 2015). First, although modern training and management usually tend to minimize permanent structure, orchards and vineyards can grow and maintain a relevant standing biomass that may represent a significant carbon stock (Morandé et al. 2017). Even if recurring

pruning limits the potential growth of the woody structure, it originates a substantial amount of debris that may accumulate as soil litter and increase soil organic fraction (Montanaro et al. 2017). Second, soil management for these systems is typically less intense than in field crops, often including cover cropping and thus promoting the slow yet steady increase of soil organic matter and its preservation (Ruiz-Colmenero et al. 2013, Wolff et al. 2018).

Recently, the interest on carbon budget of crops has been substantially expanded, including additional aspects not directly related to yield and productivity and focusing on the environmental sustainability of agriculture, e.g. soil carbon sequestration and reduction of greenhouse gases (GHG) emissions (Smith et al. 2008, Sanz-Cobena et al. 2017). Indeed, agriculture is heavily involved in the alteration of fundamental biogeochemical cycles, in particular releasing GHG to the atmosphere. Recent studies estimated that agriculture and associated land-use changes contribute to about 25% of global GHG emissions (Paustian et al. 2016), with CO₂ being responsible for 50% of average annual GHG emissions for the 2000–2009 period (Smith et al. 2014). Soil is the most important carbon pool in terrestrial ecosystems (Stockmann et al. 2013), thus efficient soil carbon management and sequestration should be pursued in agriculture to play a positive role in climate change mitigation (Lal 2013), as suggested with the ‘4 per mille Soils for Food Security and Climate’ initiative (Minasny et al. 2017). Additionally, even if not yet common, carbon storage in the field may be accounted in life cycle assessment (LCA) of agricultural products (Goglio et al. 2015), thus reducing their carbon footprint and improving environmental sustainability. Classical LCA approach has been applied to the wine sector, accounting for GHG emissions in each step of the production chain (i.e. agricultural inputs, fermentation of grapes, cellar operations, packaging and distribution), but usually neglecting the biogenic carbon budget of the vineyard (Petti et al. 2015). Only recently, this issue has been explicitly considered (Arzoumanidis et al. 2014) and guidelines for the implementation in LCA have been published (OIV 2017), but data are still scarce. In this context, our study aims at assessing the

carbon budget of a representative vineyard, providing, to our knowledge, the first long-term measurements of CO₂ fluxes.

Several efforts have been done to estimate carbon fluxes in different types of agricultural ecosystems, especially field crops (Moors et al. 2010). Vineyards have received increasing attention only in recent years due to growing interest of consumers and producers towards more sustainable wines (Smart 2010), coupled with the high market value of its final product. Research on vineyard carbon budget is today encouraged and needed to improve knowledge on the role played by this important crop in global GHG budgets (Carlisle et al. 2010). Recent studies investigated carbon content of grapevine biomass using destructive methods in order to understand plant carbon allocation and sequestration capacity (Scandellari et al. 2016, Brunori et al. 2016). Simple allometric equations to estimate carbon stocks in vineyards at the block scale (Morandé et al. 2017) and nondestructive measurements of vineyard structure with terrestrial laser-scanning technique (Keightley 2011) have been proposed to assess vineyard carbon storage. However, all these approaches only provide discrete information of vineyard status at one time, without considering carbon storage as a dynamical process. Instead, direct measurements of carbon fluxes can give detailed understanding and accurate quantification of vineyard carbon budget in relation to environmental forcing.

The study of mass and energy exchanges between atmosphere and vegetation canopies has gained great consideration in the last decades, while the parallel technological advancement allowed the monitoring of key fluxes related to crop physiology like evapotranspiration, photosynthesis and respiration (Baldocchi 2014). Studies initially performed at the leaf scale, enclosing leaves or shoots in cuvettes, were successfully extended to the ecosystem scale, being today able to measure directly the transport of mass and heat in the free atmosphere above the vegetation. These techniques belong to the wide family of the *micrometeorological methods*, which focus on the characterization of fluxes in the lower layer of

atmosphere, where they are directly determined by physiological processes of underlying vegetation. The advantages of these methods are manifold (Baldocchi et al. 1988), and here it is worth recalling that: a) they do not alter the environment around the canopy (radiation, temperature, humidity, CO₂ concentration, ventilation); b) they allow continuous and long-term measurements; c) they provide an area-integrated composite average of the exchange processes between the whole ecosystem and overlying atmosphere. On the other hand, they require flat, extended and homogeneous surfaces to collect reliable measurements. Thus, these methods are not practically suitable to compare different treatments or managements in the same field. Micrometeorological techniques can provide fundamental information on canopy functioning, casting new light on the very basic physiological processes, giving a clear picture, for instance, of the instantaneous (or seasonal) net exchange of carbon dioxide in relation to the instantaneous (or seasonal) exchange of radiation and water. The knowledge of these dynamics makes possible a thorough understanding of plant functioning and its response to environmental stresses, in the real conditions of the field.

The major part of long-term ecosystem flux measurements have been carried out using the micrometeorological technique of eddy covariance (EC) in forest sites (Aubinet et al. 2000, Goulden et al. 1996), due to the primary role played by these biomes as sink of CO₂ globally. However, other types of natural and managed ecosystems have been monitored, reaching a general overview of seasonal patterns of net ecosystem exchange (NEE) for different plant functional types (Baldocchi et al. 2008). Among them, agricultural crops are shown to achieve the highest short-term rates of carbon uptake, but their annual budget is usually positive (meaning a net loss of CO₂) or close to neutral due to long periods when the land is bare, therefore losing carbon. Only few long-term studies had been performed over woody crops (Pitacco and Meggio 2015, Zanutelli et al. 2015). These canopies are characterized by high structural complexity and, often, the floor of alleys is grassed, leading to the coexistence of two vegetation

components with different annual cycles. The cover crop is active during the mayor part of the year, while the annual cycle of grapevine begins in spring with bud break and terminates in autumn with leaf fall, followed then by winter dormancy. Therefore, vineyard NEE is determined by the combination of cover crop and vine performances along the year.

In order to study vineyard-atmosphere exchanges, an eddy covariance station was set up in a flat extensive vineyard in North-Eastern Italy. Flux measurements started in May 2014 and are still ongoing as part of a long-term monitoring program. In this work, we present the first three years of continuous measurements, from May 2014 to April 2017. General considerations on the annual carbon budget of vineyard and its inter-annual variability in relations to environmental conditions will be presented.

Materials and Methods

Site description

Field trial was carried out in an extensive flat vineyard (*Vitis vinifera*) located in North-Eastern Italy (45°44'25.80"N 12°45'1.40"E), cv *Sauvignon Blanc* grafted on 3309C. The soil (Endogleyic Calcisol) has no skeleton, presents hydromorphic features below 0.8 m and a dominant clay fraction (54%). Field capacity is 53% vol/vol and wilting point is 15% vol/vol. The vineyard, established in 2001, is about 33 ha, Guyot pruned, with rows oriented to 35-215° from North. Rows are spaced 2.2 m apart, plant spacing is 0.9 m and the canopy height at full development is 2 m, with maximum leaf area index of about 2.1 (early July). The vineyard alleys are covered by permanent grass regularly mowed during the season, while the soil below plants is chemically weeded on a strip of about 0.7 m wide. Soil cultivation is occasional and it usually consists in ripping of the inter-row one or two times per year. Winter pruning debris are shredded and left on the ground.

Eddy covariance (EC) instruments and additional meteorological sensors were installed on a self-supporting lattice tower, located in the middle of the field in order to have the longest and most homogenous fetch upwind.

Annual average air temperature is 13 °C and total rainfall is in the range of 800 to 1100 mm. These climatic features made viticulture a successful and widespread crop in the area, so far not requiring irrigation input. However, in recent years farmers started to provide additional water supply to maintain high quality production even during the recurring summer heat waves and drought spells. At our site, farmers try to increase water supply during dry periods in summer by raising the water table height using the drainage pipe system located at 1 m. During the study period, they applied this technique only twice, in late July 2015 and 2016 for about ten days.

Instrumentation

Ecosystem CO₂ flux, latent and sensible heat fluxes were monitored from May 2014 to April 2017 applying the eddy covariance technique (Aubinet et al. 2012). EC equipment consisted of a CPEC200 EC closed-path system (Campbell Scientific, Logan, UT, USA), that includes a sonic anemometer to measure the three wind components and a closed-path infrared gas analyzer (IRGA) to measure carbon dioxide and water vapor concentrations. EC instruments were deployed at 4 m height, which is two times the vegetation height at full development. Sonic and IRGA measurements were synchronously sampled and stored by a CR3000 datalogger (Campbell Scientific, Logan, UT, USA) at a sampling frequency of 10 Hz. In addition, several ancillary meteorological variables were monitored during the study period. Downward and upward, short and long wave radiation fluxes were measured using a CNR4 net radiometer (Kipp & Zonen, Delft, Netherlands) placed at 4.5 m on the top of a row, in order to have the most representative footprint view of the canopy for upward components. At the top of the tower, standard meteorological variables (air temperature, humidity and pressure, wind speed and direction, rainfall) were measured using

a WXT520 weather station (Vaisala, Helsinki, Finland). Soil water content was measured at 0.20 m depth under the row using a CS616 water content reflectometer (Campbell Scientific, Logan, UT, USA). Meteorological and soil variables were collected every 1 sec and 15 sec respectively, whereas statistics were saved every 30 min.

Data processing

Calculation of eddy fluxes was performed using EddyPro® version 6.2 (LI-COR Biosciences, Lincoln, NE, USA) open source software. Standard processing (despiking, double axis rotation and spectral corrections) for EC measurements was applied. Statistics, quality parameters and fluxes were calculated over 30-min time intervals. Periods with rain, distorted wind (coming from behind the sonic anemometer) and unrealistic values (e.g. negative fluxes during nighttime) were excluded.

The gap-filling method by Desai et al. (2005) was applied to replace missing data due to filtering, sensor malfunctioning or calibration. This algorithm replaces missing values, computing NEE as the difference between modeled ecosystem respiration (*Reco*) and gross primary production (GPP).

Results

Main meteorological variables and net ecosystem CO₂ fluxes during the three years of continuous measurements (May 2014 to April 2017) are presented in Figure 1. From the graph it can be clearly seen the annual pattern of global radiation and air temperature, with daily total radiation peaking to 30 MJ/(m² day) in clear summer days (Figure 1A). Average daily air temperature reached its maximum (29.9 °C) in July 2015, when several recurring heat waves interested the area of study, and the minimum (-3.9 °C) in January 2017 (Figure 1B). Precipitation was generally lower in winter and it showed different patterns in the other seasons in the three years. In 2014, rainfall was more evenly distributed during spring and summer, leading to higher soil moisture compared to 2015 and 2016 (Figure 1C). We express soil moisture

as fraction of available water content (*fAWC*), computed as $fAWC = (SWC - WP) / (FC - WP) * 100$, where *SWC* is soil water content, *WP* is wilting point and *FC* field capacity. *fAWC* followed precipitation patterns, reaching low values (below 40%) in summer 2015, 2016, and spring 2017.

In this manuscript, we follow the micrometeorological convention for the sign of mass fluxes, indicating with positive sign a net transport from the surface towards the atmosphere (upward) and the opposite with negative sign (downward). Thus, the net ecosystem CO₂ flux measured by eddy covariance has a positive sign when the vineyard is releasing CO₂ to the atmosphere (respiration is prevailing) and it has a negative sign when the dominant process is the uptake of CO₂ by vegetation through photosynthesis. Daily NEE showed a yearly pattern (Figure 1D): positive and small values during winter, a start of carbon uptake (negative values) in spring, a peak of absorption in early summer and a following reduction of fluxes in autumn. The NEE is mainly dependent on meteorological (solar radiation, air temperature) and environmental conditions (soil moisture), which influence plant physiological processes like respiration and photosynthesis. In fact, daily NEE was less negative or even positive during cloudy days or period of water and/or heat stress in summer, showing a strong reduction in magnitude in July and September 2015 and 2016.

EC fluxes can be integrated to obtain the pattern of ecosystem carbon assimilation through the year or the whole measurement period (Figure 1E). During spring, the cumulated carbon flux rapidly increased in magnitude, while in summer the uptake rate was lower, especially in summer 2015 and 2016 when it even decreased for short periods. In autumn, the curve stayed flat, meaning that the vineyard carbon budget was in balance. In winter, the system lost carbon, as respiration is the prevalent process taking place in this part of the year. At the end of the study period, the vineyard showed to be a net sink of carbon, with a final uptake of 403 gC/m².

The total annual carbon flux was very different between the three years of measurements. From May 2014 to April 2015, the vineyard carbon uptake was around 207 gC/m², while in the second year it was reduced to about 69 gC/m² and in the last year it was 127 gC/m². The most significant, yet very variable, seasons of the year in the annual carbon budget were spring and summer, i.e. the grapevine growing season. For this reason, we present in more detail monthly statistics of main environmental variables and carbon fluxes during the three growing seasons (May-September) in Table 1 and the seasonal time course in Figure 2. In May, meteorological conditions and carbon fluxes were similar in the three years. In June, the carbon fluxes started to diverge between years, with NEE of June 2014 being almost double respect to the other years. The greatest inter-annual variability was found during July. In July 2014, the carbon uptake of the vineyard constantly increased, while in 2015 and 2016 it almost stopped, showing a flat line in the cumulated flux (Figure 2D) and reduced values of monthly total NEE (Table 1). Average *fAWC* in the same period was relatively low and almost no precipitation was detected in July 2015, while in 2016 there were only few events followed by a hot and dry period. At the same time, daily average air temperatures were higher than in July 2014, as well as the average daytime vapor pressure deficit (*VPD*), a measure of the evaporative demand of the atmosphere. In August 2015, the uptake increased compared to July but it was still lower compared to the other years. On the contrary, in 2016 NEE increased significantly compared to the previous month, reaching values similar to August 2014. In September, the net carbon fluxes reduced in magnitude, but the vineyard uptake in 2014 was still larger than in the following years. Nevertheless, September showed to have a low impact on the seasonal carbon budget due to reduced vine activity.

The daily shape of half-hourly carbon fluxes of an active canopy is usually similar to an inverted bell curve, showing positive and flat edges during nighttime (CO₂ release by respiration) and negative values during daytime (dominating uptake of CO₂ by photosynthesis) with the peak around midday. In Figure 3,

monthly averaged daily patterns of half-hourly CO₂ fluxes during the growing seasons are presented. During June, July and August the magnitude of both negative and positive fluxes were generally larger compared to May and September. Daytime NEE fluxes were considerably greater than nighttime fluxes in every month, indicating that the vineyard was acting as a net sink of CO₂ on a daily basis. The variability between years was marked in June and July, with larger CO₂ fluxes in 2014. In particular, during July there was a difference not only in the magnitude but also in the diurnal pattern of fluxes. In July 2015 and 2016, photosynthesis reached the peak during the morning and then slowly declined through the rest of day, demonstrating an increasing water stress of the ecosystem with a typical midday depression. This behavior was still present in August 2015, but not in 2016, that instead showed a similar pattern to 2014, with a symmetrical daily pattern, without any significant depletion of photosynthesis in the afternoon. To better appreciate this, we compared diurnal patterns of CO₂ and latent heat fluxes for the same date (18 Jul) of 2014 and 2015 (Figure 4), which presented very similar incoming radiation. In 2014, the latent heat flux appeared to be non-limited, peaking in the early afternoon and resulting in a daily total evapotranspiration of 4.7 mm. On the contrary, in 2015, the maximum was observed in the morning, with a total water loss of 3.2 mm. Different daily evapotranspiration, together with peculiar patterns of H₂O and CO₂ fluxes, prove a water-limited situation in July 2015. A similar decay of carbon and water fluxes was also observed in summer 2016, when *fAWC* stayed below 40% for few weeks. Although we measure the composite response of the vineyard, grass sward was probably most affected, showing explicit signs of water stress (i.e. drydown of leaves).

The CO₂ flux measured by EC is the difference between two opposite physiological processes, photosynthesis and respiration, which are considerably larger in magnitude compared to the resultant net flux. It is common to refer to the gross uptake of CO₂ by the ecosystem as gross primary production (GPP) and to CO₂ emission as ecosystem respiration (*Reco*). In order to derive GPP from NEE measurements it

is necessary to have an estimation of *Reco* ($GPP = Reco - NEE$), that can be obtained by predictive models driven by soil temperature (Desai et al. 2005). In Figure 5, total monthly GPP and *Reco* during the growing seasons are showed. In May and September, the inter-annual variability of both GPP and *Reco* was low, while in June, July and August they were quite different between years, especially the GPP. The highest GPP was registered in June 2014 with almost 250 gC/m², on the contrary in June 2015 and 2016 it was considerably lower (around 150 gC/m²). Ecosystem respiration was higher in 2014, but the difference between years was not as marked as for GPP. In general, GPP was lower in July relative to June, whereas *Reco* increased in July 2014 and it remained almost constant in the other years. In August, GPP decreased in 2014, remained equal in 2015 and increased in 2016 compared to July, while respiration decreased. The monthly GPP/*Reco* ratio (Figure 5C) was always greater than one during the growing season, indicating that vineyard photosynthesis was larger than respiration. In general, the highest ratio was in June, a little lower in May and considerably smaller in July, August and September. The growing season 2014 and 2015 showed the higher and lower ratios respectively, with 2016 in between. The only exception was August 2016 when GPP/*Reco* ratio was much greater than the other years.

The relationship between half-hourly GPP fluxes and global radiation (R_g) is showed in Figure 6 for June, July and August of the three growing seasons. During these months, grapevine reaches its maximum development, therefore this period was selected in order to obtain a relationship between GPP and R_g , that is best representing grapevine photosynthesis. Clearly, solar radiation alone does not explain the high variability of GPP, as temperature, *VPD* and soil moisture also affect vineyard physiology. Still, a relationship between GPP and R_g is evident, with the upper boundary of data space representing the maximum potential of GPP at each radiation level. We divided the radiation range in 50 W/m² classes and fitted the maximum GPP value for each of them with an exponential saturation function:

$$GPP = GPP_{max} (1 - e^{\frac{-k}{GPP_{max}} R_g}) \quad (1)$$

where GPP_{max} [$\mu\text{molCO}_2/(\text{m}^2 \text{ sec})$] is the asymptotic value and k [$\mu\text{molCO}_2/\text{J}$] is the maximum radiation efficiency (Table 2). The year with the highest GPP_{max} was 2014, with similar values in June and July and a slight depletion in August. The other years showed lower GPP_{max} , especially in July, when it was 60% of the 2014 value. In all years, k values decreased with the season.

Vineyard fluxes, measured by eddy covariance, include vine, grass and soil CO_2 exchanges, therefore a tight correlation between NEE and vine growth or yield cannot be expected. The total yield, average pruning weight and GPP of the growing seasons are presented in Table 3. The yield was converted from fresh weight to gC based on the data published by Morandé et al. 2017, where the carbon content was found to be 10% of cluster fresh weight. Randomly sampled pruning wood was oven-dried and its dry weight converted to gC assuming that carbon is generally 50% of dry matter. The yield was very different among the three years. The highest yield was registered in 2015, when it was more than double compared to 2016 even if the GPP of the two growing seasons were of the same order. The pruning weight, on the contrary, presented a similar pattern to GPP, being 10%, 9% and 10% of GPP in each year respectively.

Discussion

In our conditions, the vineyard showed to act as a moderate net sink of carbon on annual basis, with an average yearly carbon uptake of 134 gC/m^2 . This value is lower compared to results from studies on olive (Nardino et al. 2013) and apple orchards (Zanotelli et al. 2015), but slightly larger than a citrus orchard in Spain (Maestre-Valero et al. 2017). On the contrary, our result is comparable with the annual NEE measured by Marras et al. 2015 in an irrigated vineyard in Sardinia. A previous study in a vineyard of a nearby area to our site reported higher annual carbon uptake, in the order of $800 \text{ gC}/(\text{m}^2 \text{ yr})$ (Pitacco and Meggio 2015). The difference could be related to several factors, among them soil type, training system, vigour of the plants, climate and management of the vineyard. At our site, the soil has a predominant clay

fraction and this characteristic, together with intensive heavy tractor transit, led to high compactness of the soil. Additionally, flooding and hypoxia episodes for few days mainly in winter and spring probably impacted on root system and overall vigour of the vineyard, as also observed by de Herralde et al. 2005 on Sauvignon Blanc.

However, previous studies on vineyards investigated only one year of fluxes. Several years of continuous measurements are actually needed to provide solid information on ecosystem carbon budget, especially in a context of changing climate, as reported in a paper by Baldocchi et al. 2018 comparing long-term fluxes of different ecosystems. The high inter-annual variability in yearly carbon budget found at our site, with the sink capacity in the first year being more than three times higher compared to the second year, confirms the need of long-term monitoring also for woody agricultural ecosystems (Zanotelli et al. 2015).

Carbon fluxes of the vineyard showed to be very sensitive to local meteorological conditions, in particular available water and air temperature during the growing season. From Figure 1 it is clearly visible the reduction of daily carbon fluxes during period of low available water in July and September of 2015 and 2016. Monthly average daily patterns in Figure 3 also showed a strong reduction in photosynthesis in the same months. Indeed, half-hourly CO₂ fluxes in July 2015 and 2016 deviated from the typical bell-shape curve (Turner 1990), with the vineyard reaching maximum assimilation rate in the morning and then decreasing until mid-afternoon. This pattern is typical of water stress condition and/or elevated atmospheric vapor demand: when the photosynthesis is depleted, the substomatal CO₂ concentration increases and the stomata close down. Characterization of vine leaf gas exchange under water stress has received great attention (for a comprehensive review see Lavoie-Lamoureux et al. 2017), even if analytical studies of sub-daily dynamics are scarce, usually focusing more on long-term trends (e.g. Bota et al. 2016, Pagay et al. 2016).

Rainfall is the main water supply at our study site, but during dry spells farmers try to reduce the stress by increasing the water table height using the drainage pipe network. However, in our case this was clearly insufficient to maintain adequate soil moisture in July 2015 and 2016, when the atmospheric evaporative demand was considerably high. June 2015 had over 200 mm of rain, but the larger part was given by two intense events of 98 and 75 mm/day respectively, separated only by one day. Due to low soil permeability, most of this precipitation was then probably lost by surface runoff. The combination of “opposite” extreme weather events, like heavy but irregular precipitation followed by heat waves, showed to have a strong negative effect on vineyard carbon budget. On the contrary, under non-limiting water conditions, like in 2014, the vineyard presented the strongest carbon sink capacity.

Like for other ecosystem types, the growing season showed to be crucial for the annual carbon budget and this is in agreement with Baldocchi et al. 2018, showing that the variability in ecosystem photosynthesis is the dominant factor for the inter-annual variation in NEE. Indeed, at our site, higher monthly GPP in 2014 were associated to greater net uptake. The inter-annual variability in GPP/*Reco* was not as marked as for GPP. The larger GPP in 2014 was linked to higher respiration fluxes, probably connected to greater amount of biomass in the ecosystem compared to the other years, as indicated by the higher pruning weight.

The yield was quite variable among the three years and it was not correlated with total GPP or NEE of the growing season, as it was also found by Zanutelli et al. 2015 in an apple orchard. However, we found that the ratio of pruning weight to GPP was almost constant in the three years, but it was more variable when compared to NEE. This indicates that the gross photosynthesis flux was positively correlated to vine vegetative growth, but when respiration is also taken into account, the relationship becomes less clear. The reason could be related to several factors, first of all that the eddy covariance method measures net ecosystem fluxes, accounting for vine, cover crop and soil compartments all together.

Conclusion

We showed that the vineyard could act as a moderate carbon sink on annual basis, even if the carbon uptake was quite variable among years due to the influence of environmental conditions (especially air temperature, precipitation and soil moisture). Indeed, climate variability and the increased frequency of extreme weather events can have a strong impact on the carbon budget of vineyards, along with site specific management practices (e.g. cover cropping, soil tillage, canopy management). Our findings demonstrate the potential of woody crops to behave as a carbon sink on the medium-long term, and we suggest this should be taken into account in national and international agricultural and environmental policies complementing standard Life Cycle Assessment of the wine production chain. Long-term studies of CO₂ fluxes over vineyards in different climatic regions are therefore fundamental to assess the role of viticulture in the global carbon budget and to refine management techniques, improving its environmental sustainability.

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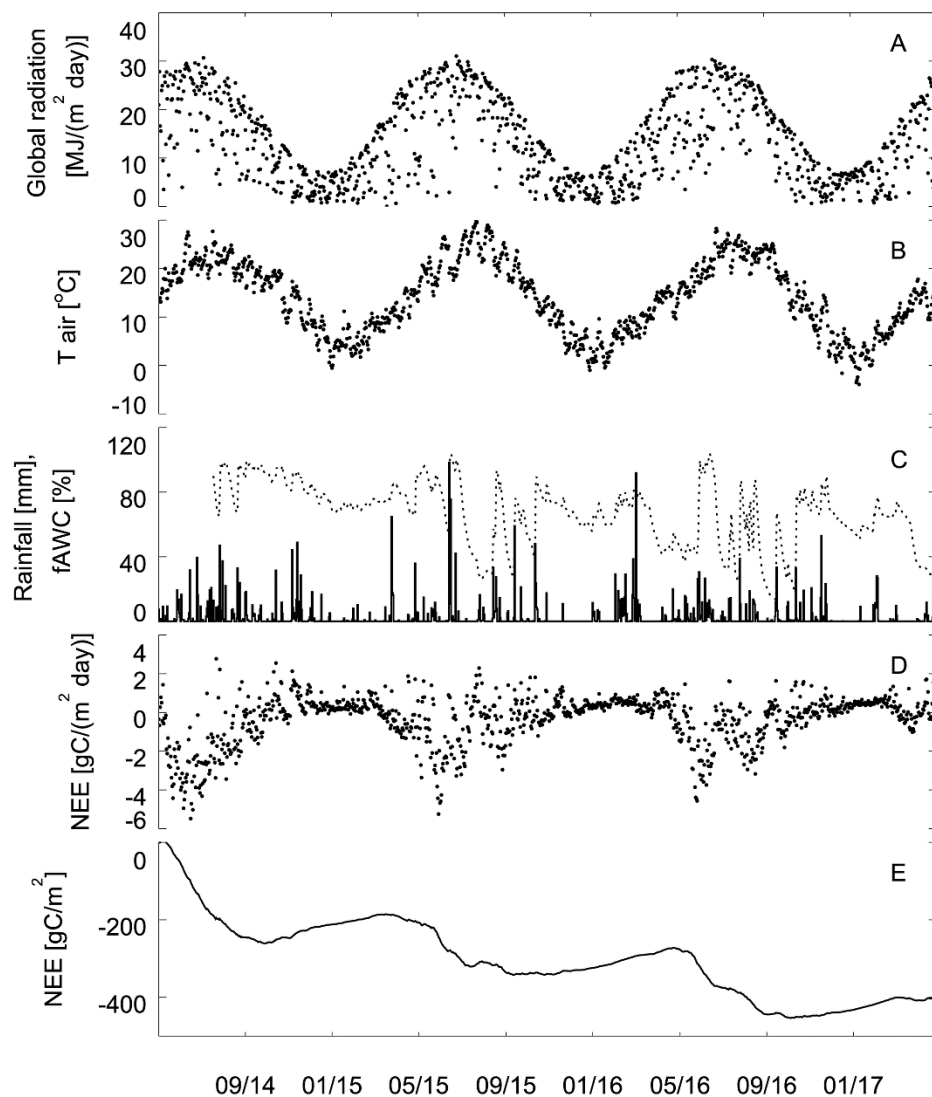


Figure 1 Time courses during the three years of measurements of (A) daily total global radiation, (B) daily average air temperature, (C) daily total rainfall and average fraction of available water content (*fAWC*), (D) daily net ecosystem exchange (NEE) flux, and (E) cumulated NEE.

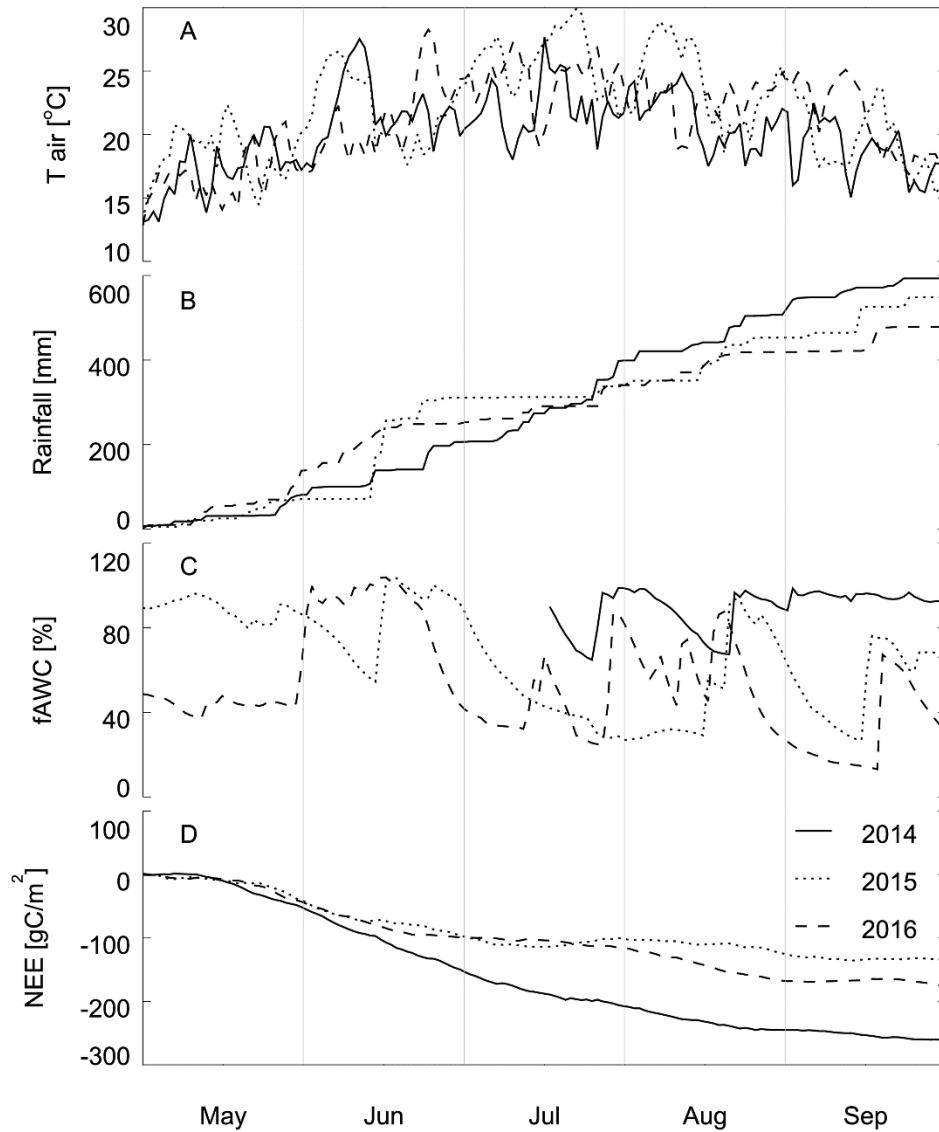


Figure 2 Seasonal trends of (A) daily average air temperature, (B) cumulated rainfall, (C) daily average fraction of available water content ($fAWC$), and (D) cumulated net ecosystem exchange (NEE) in the growing seasons of 2014, 2015 and 2016.

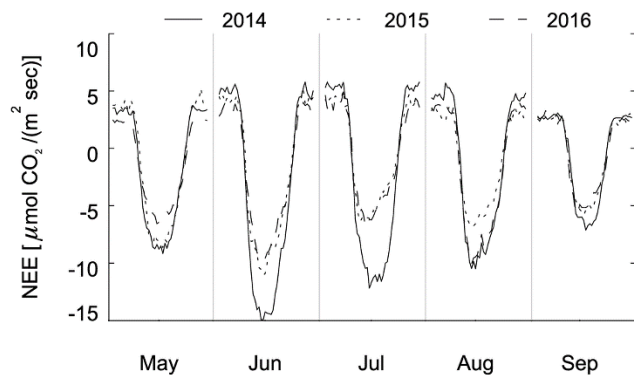


Figure 3 Monthly average daily patterns of half-hourly net ecosystem exchange (NEE) in the growing seasons of 2014, 2015 and 2016.

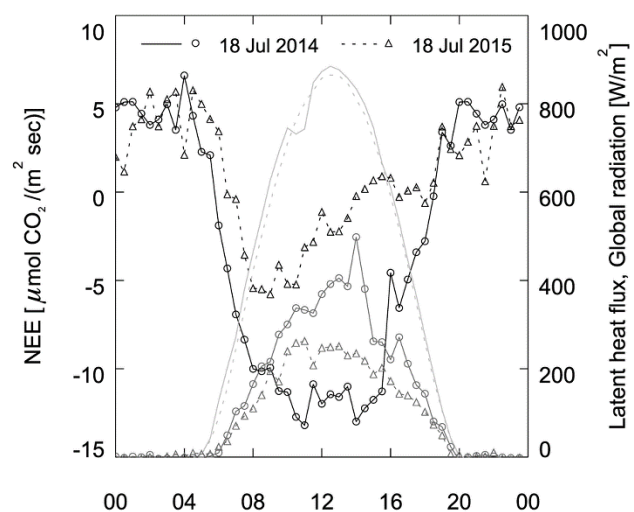


Figure 4 Daily patterns of half-hourly net ecosystem exchange (NEE) (black), latent heat flux (grey) and global radiation (light grey) on 18 Jul 2014 (solid line) and 18 Jul 2015 (dashed line).

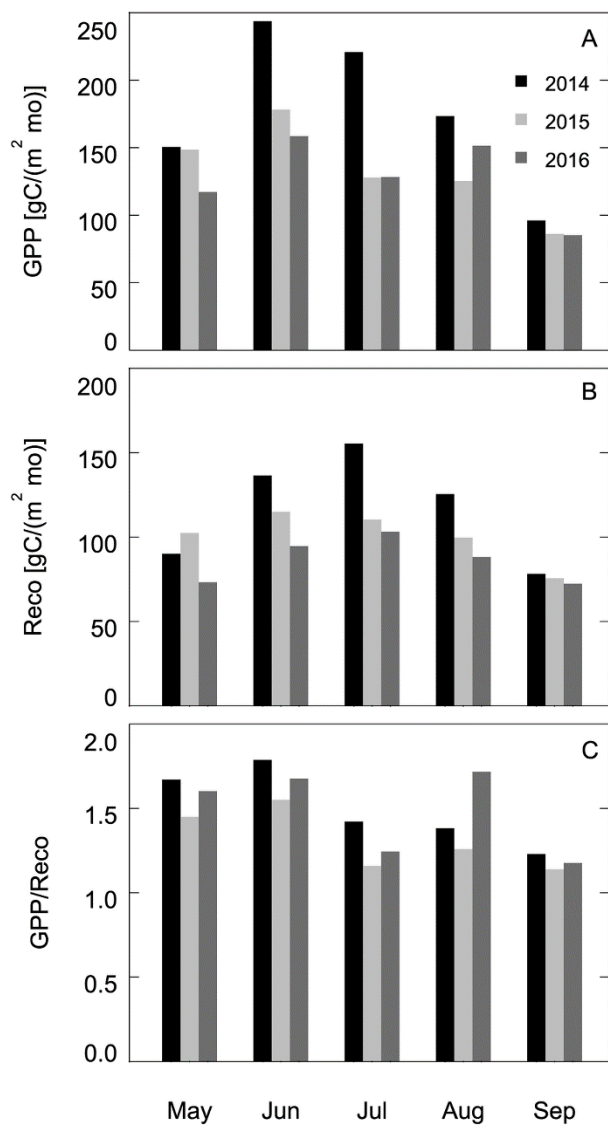


Figure 5 Seasonal trends of monthly (A) gross primary production (GPP), (B) ecosystem respiration (*Reco*), and (C) GPP to *Reco* ratio in the growing seasons of 2014, 2015 and 2016.

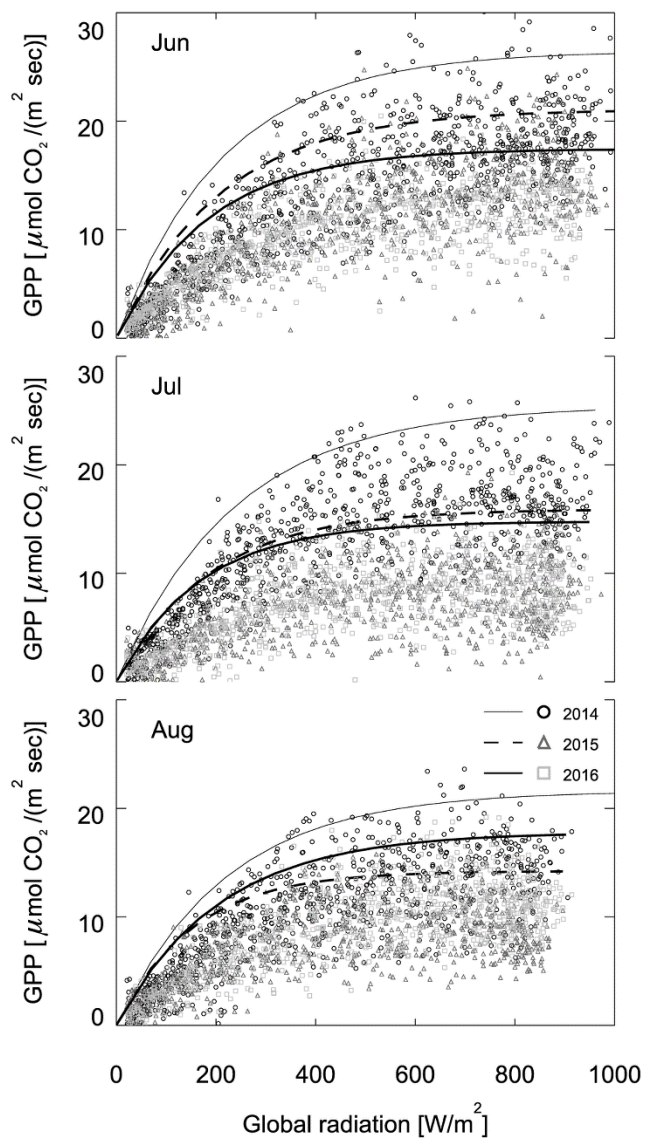


Figure 6 Relationship between half-hourly gross primary production (GPP) and global radiation in June, July and August of 2014, 2015 and 2016. Lines represent modeled maximum GPP for each radiation value using the radiation response model (Equation (1)).