Disentangling the carbon budget of a vineyard: The role of soil management

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ABSTRACT

The environmental sustainability of viticulture can be enhanced with the application of conservative management practices (e.g. resident vegetation or cover crop on the inter-row), which can lead to an increase of soil carbon (C) sequestration. However, studies disentangling the vineyard C budget are still very scarce. In this context, comparing vineyard net ecosystem CO_2 exchange (NEE) with soil fluxes is especially useful. From January 2015 to August 2016, we continuously monitored vineyard NEE with the eddy covariance method and ground CO_2 fluxes with an automated chamber system in a commercial vineyard in North Eastern Italy. At the site, inter-rows are covered with resident herbaceous vegetation, however, due to low soil permeability, soil cultivation (ripping or tillage) was performed on alternate alleys in autumn and, sometimes, spring in order to improve water infiltration. Measured annual soil respiration was comparable, but lower, to values estimated by previous studies in vineyards and the net uptake of the grass cover laid in the middle of yearly C budget range reported in the literature for grasslands. At the end of the measurement period, the vineyard ecosystem showed to be a net sink of CO_2, absorbing around -233 gC m^{-2}. However, the C sequestration could have been much greater if no soil cultivation had been applied. Indeed, the ground compartment was a source of CO_2, but without inter-row cultivation it could have been a net sink, with an overall vineyard C budget of about -421 gC m^{-2}. This confirms that grass cover of the inter-rows can play an important role in the C budget of woody crops. Additionally, the pattern of C fluxes reveals that the activity of herbaceous vegetation in summer decreased well before vines, thus reducing water competition during dry periods. These results provide important information for the tuning of management practices aimed at improving the environmental sustainability of viticulture.

1. Introduction

The role of agriculture in the global balance of greenhouse gases (GHG) has received a lot of attention in the last decades. Land cover change, husbandry and abundant use of technical input (e.g. fuel, fertilizers, pesticides, and herbicides) are estimated to be responsible of 24% of anthropogenic GHG emissions (Smith et al., 2014), while the possible sink capacity of most crops is commonly considered as limited or nil. Carbon dioxide represents about 50% of these emissions, and the increase of soil carbon (C) sequestration is a promising option for agriculture to play a role in climate change mitigation (Lal, 2007; Paustian et al., 2016). Soil is the most important C pool in terrestrial ecosystems, thus small changes in soil organic carbon (SOC) could reflect in a substantial modification of atmospheric CO_2 concentration (Stockmann et al., 2013). The SOC degradation rate in cultivated land is usually one order of magnitude greater than under forest (Guo and Gifford, 2002). Indeed, after long time of intensive cultivation practices, the C pool of agricultural soils has been substantially depleted,

showing today a large unfilled C storage capacity (Lal, 2013). The latter, even being a negative result of decades of intensive cultivation, can represent a strategic opportunity for agriculture, that could play a primarily role in C re-sequestration. This was recently recognized by the '4 per mille Soils for Food Security and Climate' initiative launched at the COP21, which aims to increase SOC stocks by 0.4% per year, and agricultural lands have the higher potential to reach this objective (Minasny et al., 2017). Even if most of CO_2 uptake in agriculture is not properly long-term, along with reduction of emissions, it could be useful to buffer the increase of atmospheric CO_2 with a strategic short-term effect (Wollenberg et al., 2016). Nevertheless, in order to verify and reinforce the potential of agriculture, the quantification of net C exchanges of agroecosystems is necessary to understand soil organic matter (SOM) build-up, stabilization and degradation processes. Indeed, the monitoring of CO_2 fluxes is fundamental to correctly account for C uptake or release by different agroecosystems in common policies (e.g. Common Agricultural Policy of the EU). In any case, a greater knowledge of CO_2 flux dynamics could promote the implementation

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and accountability of management practices aimed to reduce soil C loss and/or increase sequestration.

Carbon stocks in soils can be enhanced by reducing decomposition rates and/or increasing inputs of organic matter (Paustian et al., 2016). It is commonly recognized that soil cultivation enhances SOM oxidation, leading to higher soil respiration rates (Lal, 2013). However, few studies, comparing CO_2 fluxes of tilled and no or reduced tillage soils, found greater annual or seasonal emissions from the latter after several years of treatment (Dong et al., 2017; Lognoul et al., 2017). They attributed higher respiration rate to the greater SOM content in soil upper layers under reduced or no tillage. Nevertheless, most studies found long-term increase of SOM and SOC with soil conservation practices (Almagro et al., 2017; Lu et al., 2016; Montanaro et al., 2017b; Zehetner et al., 2015). Even if conservative soil management is promising for agricultural C sequestration on the long-term, the effect of tillage on the annual C budget of bare soil has been shown to be low (Almagro et al., 2017). Indeed, CO_2 emission increases immediately after tillage, but this effect lasts just for few hours/days, then returning to pre-tillage soil respiration values (Dong et al., 2017; Steenwerth et al., 2010; Wolff et al., 2018). For this reason, the reduction of soil cultivation alone seems to be not so effective for GHG mitigation in the short-term (Powlson et al., 2014) and it should be combined with other conservative management practices.

In this respect, one of the most promising actions is the use of cover crops, which represents an active way of CO_2 uptake from the atmosphere and it involves many additional advantages. Indeed, cover crops can provide several ecosystem services related to improvement of soil quality and its hydrological properties, having also a positive impact on climate change through reduction of GHG emissions and increase of soil C sequestration (Blanco-Canqui et al., 2015; Lal, 2015). In annual productions, cover crops are temporary planted between two cycles, whereas in woody crops (i.e. orchards, vineyards, and olive groves) they can potentially be permanent in the inter-row. In the first case, cover cropping has been shown to increase SOC (Olson et al., 2014; Poeplau and Don, 2015), even if plants are usually removed after few months. On the contrary, vegetation cover on the alley of woody crops can be let undisturbed for decades, increasing the biomass and overall soil C stock. Indeed, the use of cover crops in woody cropping systems was found to be the most promising actions for agriculture to mitigate GHG emissions in Mediterranean agroecosystems (Pardo et al., 2017), representing an opportunity to increase the sustainability of this peculiar agricultural sector (Márquez-García et al., 2013; Wolff et al., 2018). Additionally, woody crops grow and maintain a relevant standing biomass that may represent a significant C stock itself (Morandé et al., 2017). The C budget of perennials has received increasing attention in the last years, with several studies aimed at assessing their role in the global GHG budget (Brilli et al., 2016; Chamizo et al., 2017; Montanaro et al., 2017a; Pardo et al., 2017; Scandellari et al., 2016; Vicente-Vicente et al., 2016; Zanotelli et al., 2015). In particular, research on GHG emissions and C sequestration of vineyards is encouraged (Schultz, 2010; Carlisle et al., 2010) given the few information available (Brunori et al., 2016; Keightley, 2011; Marras et al., 2015; Morandé et al., 2017; Vendrame et al., 2019), viticulture economic relevance and growing interest of consumers and producers towards more sustainable wines (Smart, 2010).

Indeed, vineyard is a peculiar agricultural ecosystem where two crops (grapevine and resident vegetation or cover crop) might coexist and proper tuning of management practices can greatly impact environmental sustainability. The use of cover crops in the inter-row of vineyards showed to increase the C stock in soil upper layers (Agnelli et al., 2014; Peregrina et al., 2012; Wolff et al., 2018). Additionally, previous studies collected in a review by Garcia et al. (2018) mentioned further ecosystem services: soil protection, weed control, pest and disease regulation, water supply, water purification, field trafficability and soil biodiversity. However, in several viticultural areas, especially the ones exposed to water shortage (e.g. Mediterranean), cover crops are commonly not used to reduce water consumption. Nevertheless, studies in vineyards showed that the competition for water between vine and cover crop is limited (Steenwerth et al., 2016), as vines tend to adapt the root system developing deeper roots (Celette et al., 2008; Klodd et al., 2015). Additionally, the presence of vegetation on the inter-rows reduces surface runoff (Biddoccu et al., 2017; Márquez-García et al., 2013; Napoli et al., 2017), enhancing water infiltration in the soil profile (Ruiz-Colmenero et al., 2013) and allowing a better storage of rainfall during winter (Palese et al., 2014). This could represent an important benefit for climate change adaptation and partly compensate for the extra evapotranspiration by the cover crop (Celette et al., 2008). Vineyard soils are subjected to compaction due to frequent passing of heavy tractors and the presence of cover crops on the alleys can alleviated this effect (Ferrero et al., 2005), increasing trafficability of the inter-row. Another important aspect is the mitigation of soil thermal regime, where the cover crop reduces soil temperature acting as an insulating layer (Pradel and Pieri, 2000) and limiting heating. This can directly affect soil CO_2 fluxes, which showed higher sensitivity to temperature in tilled soils, indicating that cultivation may increase soil C vulnerability in future climate scenarios (Almagro et al., 2017). In this context, it is fundamental to study soil CO_2 emission and, at the same time, net CO_2 uptake by the cover crop. The long-term monitoring and quantification of both fluxes can increase the understanding of soil C budget in response to environmental variables and management practices.

Measurements of soil CO_2 fluxes are usually performed using a chamber placed over a PVC or metal collar inserted into the soil surface. There are several methods to derive fluxes, including: monitoring the variation of CO_2 concentration over time (closed system or non-steady state); quantifying the difference in CO_2 concentration between the chamber inlet and outlet for a known flow of air (open system or steady state); or absorbing CO_2 in the chamber using chemicals (static chambers) (Ryan and Law, 2005). With the application of a transparent chamber enclosure, closed and open systems become also suitable to measure net CO_2 flux of herbaceous vegetation. Only few studies have been conducted on soil respiration fluxes in vineyards or orchards (Bertolla et al., 2014; Carlisle et al., 2006; Franck et al., 2011; Scandellari et al., 2015; Turrini et al., 2017; Wolff et al., 2018), and most of them carried out sporadic measurements every few weeks or once a month. Indeed, to our knowledge, no continuous direct measurements of cover crop net CO_2 fluxes in woody cropping systems are available. Soil chambers are useful to evaluate the C dynamics of ground compartment, but they do not provide a complete picture of C fluxes. A thorough understanding of ecosystem C budget and its partitioning requires also measurements at the field scale to quantify the net CO_2 exchange of the whole ecosystem (NEE). These can be obtained applying the micrometeorological method of eddy covariance (EC) (Aubinet et al., 2000). Only the combination of methods at different measurement scales can provide an effective insight of vineyard C pools and fluxes. In this study, we carried out long-term monitoring of ground and ecosystem CO_2 fluxes in a vineyard of North Eastern Italy with inter-rows covered by spontaneous herbaceous vegetation. The aim of the study was to characterize ground CO_2 fluxes, disentangling the C budget of the vineyard and clarifying the role of cover crops. This is fundamental to advance basic knowledge of composite cropping systems and improve management practices towards a more sustainable and efficient agriculture.

2. Materials and methods

2.1. Description of study site

The study was carried out in a commercial vineyard (*Vitis vinifera,* cv. *Sauvignon Blanc* grafted on 3309C) located in North Eastern Italy (45°44′25.80″N 12°45′1.40″E). The vineyard, established in 2001, is trained to Vertical Shoot Position trellis system and Guyot pruned.

Rows are 2.2 m apart and oriented to 35–215 °N, while plant spacing is 0.9 m. Canopy height at full development is around 2 m. The vineyard is rainfed, and alleys are covered with resident herbaceous vegetation (mainly dicots like *Taraxacum officinale*, *Trifolium* spp., *Plantago* spp. and fewer graminoids) mowed once or twice per year (according to summer rainfall), except for a strip about 0.6 m wide on the row that is chemically weeded. Soil is ripped or tilled on alternate alleys in late summer. When tillage is applied, alleys are then rotary tilled in early spring.

The vineyard is located in an alluvial plain, and the area is a lowland reclaimed in the 1930′s. Soil texture is 54% clay, 22% silt and 24% sand, with 1.53% of organic carbon, 0.21% of total nitrogen and pH 8.24. Soil bulk density is 1.35 g cm^{-3} on the row and 1.6 g cm^{-3} in the inter-row, due to heavy tractor traffic in the alley. The soil (Endogleyic Calcisol (WRB, 2014)) has no skeleton and presents hydromorphic features below 0.8 m. Field capacity is 53% vol/vol and wilting point is 15% vol/vol. The soil permeability is in the class of 0.36–3.6 mm h^{-1}, that is quite low according to the Soil Survey Manual of USDA (2017).

Climate is characterized by warm summers and relatively cold winters (Köppen climate classification: Cfb), with average annual temperature of 13 °C (summer and winter average temperatures 22 °C and 3.3 °C, respectively). Precipitation is quite homogeneous throughout the year with two peaks (the main in autumn and secondary in spring), with a total annual average ranging between 800 and 1100 mm.

This climate 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 summer spells by raising the water table 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.

2.2. Soil CO_2 flux measurements

An automated dynamic soil CO_2 flux system with multiplexer (LI-8100 and LI-8150, Li-Cor Biosciences, Lincoln, NE, USA) was deployed on two adjacent alleys in the center of the vineyard. In order to allow an undisturbed continuous monitoring, tractor traffic and soil cultivation in the survey area was avoided. This area (20 m x 5 m) was manually managed (mowing, spraying, topping, harvesting, fertilizing) similarly to the rest of the vineyard. The system included three chambers: two dark-dome chambers (Li-Cor LI-8100-104) and one clear-dome chamber (Li-Cor LI-8100-104C). At each measurement location, a PVC collar (20 cm diameter) was inserted into the soil about two months before measurement start, in order to reduce the effect of soil disturbance on fluxes. The collars, 11 cm high, were inserted for about 5 cm into the soil. Soil temperature (Ts) was measured with thermistors and soil water content (SWC) with EC-5 probes (Decagon Devices, Pullman, WA, USA), installed at the side of each chamber about 5 cm below the surface. Soil moisture was expressed as fraction of available water content ($fAWC$), computed as $fAWC = (SWC-WP)/(FC-WP)*100$, where WP is wilting point and FC field capacity.

To measure row soil respiration (Rs_r), one dark chamber was placed on the chemically weeded strip in the row (Fig. 1). The second one was installed in the middle of the alley on a plot (60 cm × 60 cm) kept clear of grass to mimic cultivated soil condition, measuring inter-row bare soil respiration (Rs_i). This plot was set up about two months before system deployment to avoid possible bias caused by root decomposition. The borders of the plot were regularly cut vertically to about 15 cm depth, in order to avoid the entrance of grass roots from the side and vegetation growing on the plot was regularly cleared by hand. The transparent chamber was installed on the grass sward in the alley to measure the net CO_2 exchange resulting from respiration and photosynthesis of the surface (NEE_{grass}). Here, we follow the micrometeorological convention for the sign of mass fluxes: a positive flux means release of CO_2 from the surface towards the atmosphere, while a negative flux indicates uptake of CO_2.

The monitoring was carried out from January 2015 to August 2016, collecting CO_2 flux measurements every 30 min. For each chamber, the measurement cycle lasted 2 min and 35 s, deriving the flux from the variation of CO_2 concentration (recorded every second) in the chamber during this interval (excluding the first 45 s, dedicated to system pre-purge).

2.3. Soil CO_2 flux data processing

The timeseries of raw fluxes was filtered for outliers and spikes. Resulting gaps in soil respiration (Rs) were filled using Lloyd and Taylor (1994) model:

$$Rs = R_{ref}\, exp^{E_0(\frac{1}{T_{ref}-T_0} - \frac{1}{T_S-T_0})} \tag{1}$$

where R_{ref} is respiration at the reference temperature (T_{ref}, 10 °C), E_0 is the activation energy related to Arrhenius equation and T_0 is kept constant at 227.13 K as in Lloyd and Taylor (1994). We fitted R_{ref} and E_0 using Marquardt algorithm. Gaps in daytime fluxes from clear chamber were filled estimating NEE_{grass} by fitting a rectangular hyperbolic light-response function (Falge et al., 2001):

$$NEE_{grass} = \frac{-b_1 Rg}{b_2 + Rg} + Rs_i \tag{2}$$

where Rg is the incoming short-wave radiation, b_1 and b_2 are fitted parameters (respectively: b_1 is maximum gross primary production and b_2 the level of Rg for which gross primary production is half of the maximum). The timeseries of Rs and NEE_{grass} were split into monthly datasets and model parameters were fitted for each month.

The overall vineyard soil respiration (Rs_{vin}) was calculated as the weighted average between Rs_i and Rs_r, $Rs_{vin} = A_i\, Rs_i + A_r\, Rs_r$, where A_i (0.73) and A_r (0.27) are inter-row and row fractional areas respectively. The vineyard ground net CO_2 flux was calculated as $NEE_{ground} = A_r\, Rs_r + A_i\, (A_g\, NEE_{grass} + (1-A_g)\, Rs_i)$, where A_g is the fractional area covered by grass. Soil cultivation, performed on every other alley in the vineyard, regularly disrupted grass sward. In September 2014, soil ripping affected half of the inter-row and, at the beginning of the study period, A_g was still reduced roughly to 75% of full cover. On the contrary, soil tillage carried out in September 2015 and rotary tillage in April 2016 interested the whole alley, reducing A_g to 50%. In June of both years, the herbaceous vegetation in the inter-row reached full cover again.

2.4. Ecosystem CO_2 flux measurements

The vineyard net ecosystem exchange (NEE_{vin}) was measured during the whole study period applying the eddy covariance (EC) method. This technique allows for long-term monitoring of vegetation-atmosphere exchanges at the ecosystem scale, providing spatially and temporally averaged CO_2, water vapor and sensible heat fluxes every 30 min. The tower was deployed in the monitoring area and equipped with a closed-path EC system CPEC200 (Campbell Scientific, Logan, UT, USA) placed at 4 m height. For more information on EC setup and data processing refer to Vendrame et al. (2019). Main meteorological variables were measured with a WXT520 weather station (Vaisala, Helsinki, Finland), and the radiation fluxes with a CNR4 net radiometer (Kipp & Zonen, Delft, The Netherlands).

3. Results and discussion

3.1. Meteorological conditions during the study period

The monthly average air temperature (Ta) (Fig. 2) during the study period was about 1 °C higher compared to the climatological value of
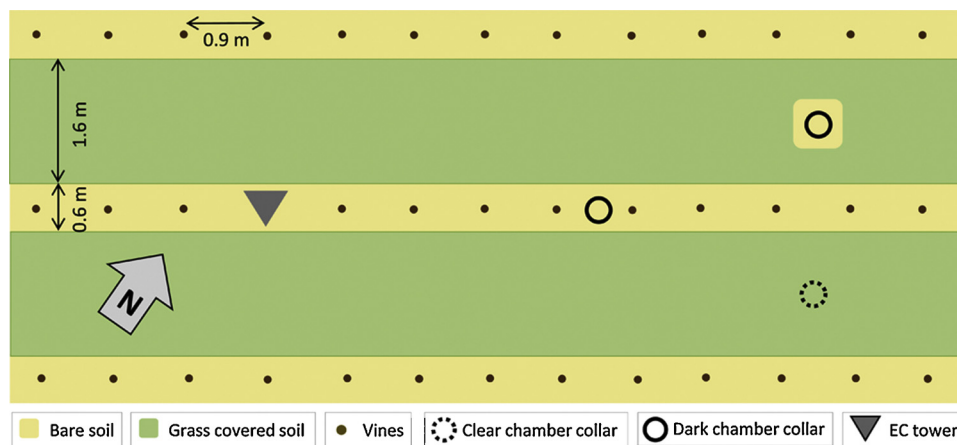
Fig. 1. Schematic representation of the area in the vineyard where eddy covariance tower (triangle) and soil chamber collars (solid circles: dark chamber; dotted circles: clear chamber) were installed. Light yellow and green areas represent bare soil and spontaneous vegetation cover, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the last 20 years. The greatest anomaly was recorded in July 2015, with a monthly mean temperature 2.7 °C higher than the 20-years average. Indeed, during this month several heat waves reached the area, with a maximum air temperature of 37 °C on July 22.

Heat waves were clearly detectable also in soil temperature time-series. Bare soil temperature (Ts_{bare}) was directly influenced by incoming radiation showing substantial heating during clear days, while soil temperature under grass (Ts_{grass}) generally presented lower values (Fig. 3a). The greatest difference was in summer 2015, with Ts_{bare} being 11 °C higher than Ts_{grass} in the afternoon of July 22. In summer 2016, this effect was not detected because of lower grass density above the sensor. In general, during heat waves mean daily Ts_{grass} was lower than Ta indicating a mitigating effect by grass cover.

The total precipitation in the two hydrologic years did not differ significantly from the 20-years mean, with 1033 mm in 2014/2015 and 1029 mm in 2015/2016. Nevertheless, the rainfall distribution was quite different from average. Indeed, during the study period, there were only 6 rainy days less, but precipitation was concentrated in few months. This caused an excess of rain in some months (e.g. June 2015 + 179%, February 2016 + 242%, March 2016 + 76%) and a depletion in others (e.g. in 2015 January −82%, July −64%, December −100%) (Fig. 2).

Soil moisture followed precipitation patterns, reaching low values ($fAWC$ around 20%) in July 2015, January, July and September 2016 (Fig. 3b). Few heavy rain events in June 2015 showed to increase temporarily the soil moisture content, but during the following dry and hot spell it was depleted in few days. This may indicate that most of the rainfall was lost by runoff and evaporation from the surface, because of low soil permeability.

3.2. Soil CO_2 fluxes

The annual pattern of daily soil respiration (Fig. 3c) followed soil temperature trend, with a maximum in early summer and minimum in winter. Low winter fluxes started to increase in March, reaching a peak in June, and then decreased in September. CO_2 effluxes measured on the row (Rs_r) and on the alley (Rs_i) showed similar patterns throughout the study period. In general, Rs_i was greater than Rs_r, with mean values of 1.05 and 1.12 gC m^{-2} day^{-1} respectively. This might be related to higher density of grapevine fine roots in the inter-row, which commonly have greater respiration rates compared to coarser roots (Franck et al., 2011). Indeed, the larger difference between Rs_i and Rs_r, was observed in spring of both years, when root activity increases just before bud break (Wolff et al., 2018).

The mean overall vineyard soil respiration (Rs_{vin}) during the study period was 1.14 gC m^{-2} day^{-1}, with a minimum of 0.05 gC m^{-2} day^{-1} in February 2016 and a peak of 3.51 gC m^{-2} day^{-1} in June 2015 (Fig. 3d). In general, respiration fluxes stayed below 1 gC m^{-2} day^{-1} when soil temperature was lower than 10 °C. These results are comparable with the values estimated by Franck et al. (2011) in a Chilean vineyard, where the mean daily respiration was 1.48 gC m^{-2} day^{-1}. This flux, slightly greater compared to our measurements, was probably resulting from higher respiration rates due to milder winter air temperature in their conditions. On the contrary, their summer peak is very similar (3.26 gC m^{-2} day^{-1}) to what we found.

As reported before, CO_2 effluxes generally followed seasonality and especially temperature pattern. However, under specific circumstances, fluxes tended to deviate, presenting extremely high or low values. Usually, the latter happened under heavy rainfall or very dry conditions, whereas, once optimal soil moisture content was reached again,
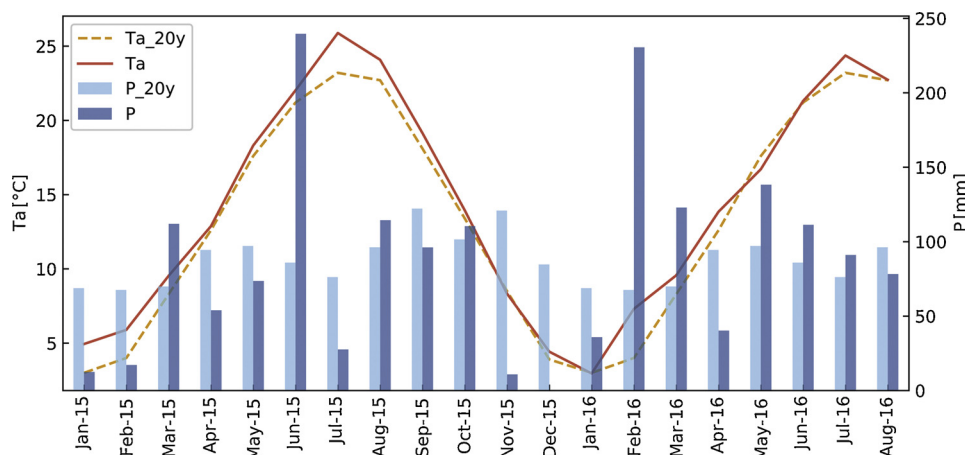

Fig. 2. Monthly average air temperature (Ta, solid red line) and monthly total precipitation (P, blue bars) during the study period and historical 20-years mean (Ta_20y, dashed orange line and P_20y, light blue bars). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
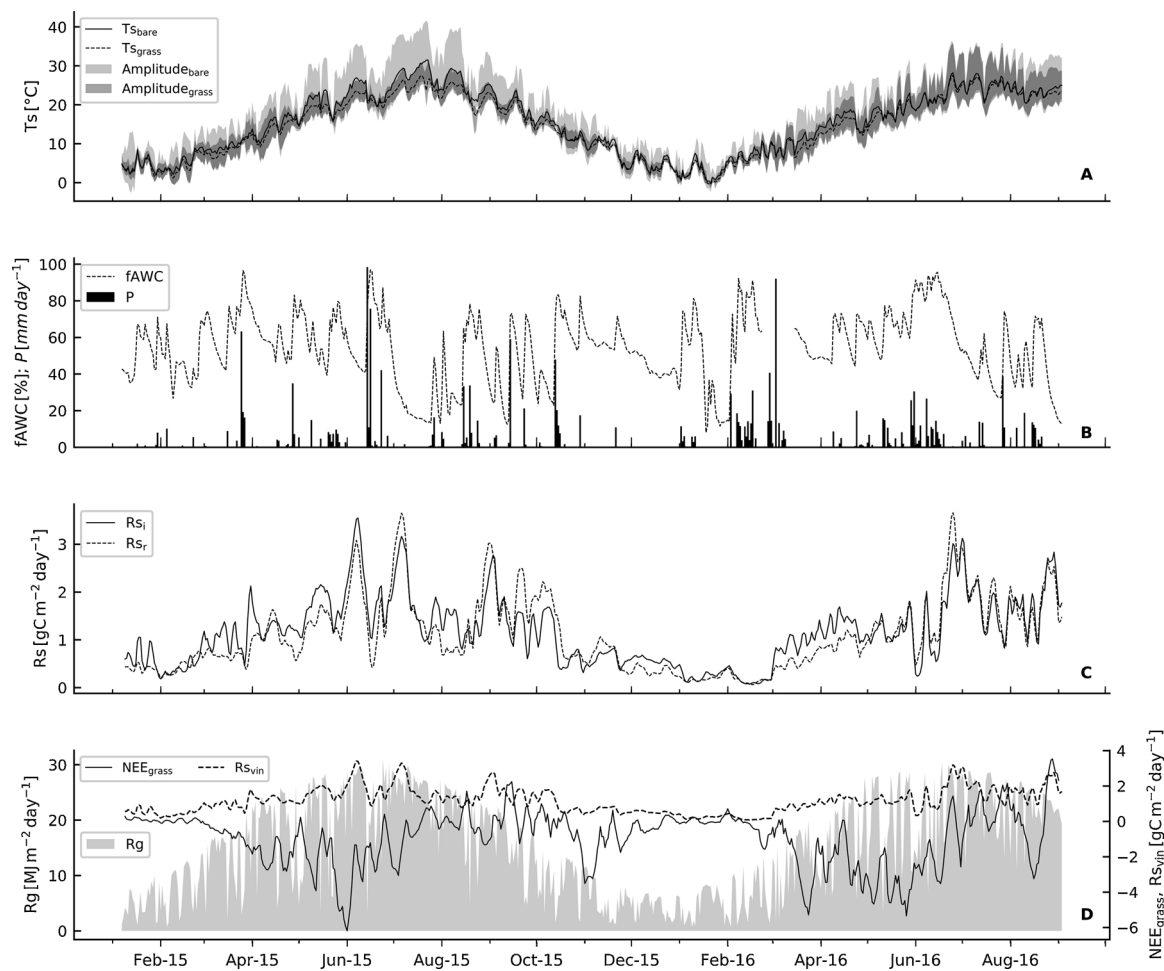
Fig. 3. a) Daily average soil temperature of bare soil (Ts_{bare}, solid line) and grass-covered soil (Ts_{grass}, dashed line). Areas correspond to daily amplitudes of bare (light grey) and grass-covered soil (grey) temperature, i.e. difference between max and min daily temperatures. b) Daily total precipitation (P, bars) and mean fraction of available soil water content ($fAWC$, dashed line).c) Row (Rs_r, dashed line) and inter-row (Rs_i, solid line) daily soil respiration. d) Grass daily net CO_2 flux (NEE_{grass}, solid line) and vineyard mean soil respiration (Rs_{vin}, dashed line), calculated as weighted average of Rs_i and Rs_r. Grey area indicates daily total global radiation (Rg).

fluxes returned to the typical values of the season. Indeed, past studies reported that optimal conditions for soil respiration are found at intermediate soil water contents (Davidson et al., 2000; Flechard et al., 2007). At our site, depletion of fluxes after heavy rainfall events was probably related to the low soil permeability. Saturation of upper soil layers and waterlogging at the surface affected the rate of gaseous diffusion within the soil profile (Carlisle et al., 2006; Davidson and Trumbore, 1995; Freijer and Leffelaar, 1996; Hirano et al., 2003), leading to transient hypoxia conditions (Linn and Doran, 1984; Oberbauer et al., 1992) and reducing respiration rates. At the opposite extreme (i.e. dry soil), CO_2 fluxes can be inhibited due to the reduction of CO_2 production by both microbes and roots (Curiel Yuste et al., 2007; Davidson et al., 2000; Orchard and Cook, 1983). Depletion of microbial respiration is likely linked to the reduction of soluble organic substrates used as energy sources by heterotrophic microorganisms (Billings et al., 1998; Davidson et al., 2000; Linn and Doran, 1984), while water stress slows down root metabolism (Burton et al., 1998; Carey et al., 2016; Huang et al., 2005). In our case, Rs_{vin} was limited by drought conditions when $fAWC < 20\%$ (Fig. 4a), as also reported by Rey et al. (2002) and Urbanek and Doerr (2017).

Looking in more details at the short-term dynamics (30 min fluxes, data not showed), we sporadically observed anomalous CO_2 bursts during and immediately after heavy rainfall events, especially when succeeding drought periods. This phenomenon was probably related to the effect of water entering soil cracks and macropores, suddenly displacing CO_2 previously accumulated in air space (Carlisle et al., 2006;

Testi et al., 2008). After these peaks, soil efflux returned within normal range, but achieving higher values than before because of the re-activation of heterotrophic respiration (Rey et al., 2005; Steenwerth et al., 2010). Eventually, if precipitation was abundant and soil saturation was reached, previously explained hypoxic conditions also occurred. Then, once water started to drain, a negative pressure was produced in the macropores, pumping air into the soil and causing anomalous negative fluxes (Ryan and Law, 2005), leading to spurious CO_2 absorption. All these unrealistic values were filtered out and gap-filled to calculate total daily fluxes.

At the end of the study period, the cumulated soil respiration was about 693 gC m^{-2}, and the annual C efflux was 417 gC m^{-2} $year^{-1}$ in 2015. Following a measurement protocol similar to our research, Scandellari et al. (2015) conducted a continuous monitoring of soil CO_2 fluxes in an organic apple orchard, obtaining a soil respiration of 981 gC m^{-2} $year^{-1}$. To our knowledge, only few studies have been carried out on the annual soil carbon budget of vineyards, performing occasional measurements per month and obtaining the annual budget from estimated daily fluxes. The annual respiration rates reported in these studies are generally higher compared to our results. Franck et al. (2011) estimated an annual flux of 540 gC m^{-2} $year^{-1}$ in a vineyard with similar soil texture but lower total carbon. Carlisle et al. (2006) obtained a yearly efflux of 700 gC m^{-2} $year^{-1}$ in a Californian vineyard with analogous total C content to our soil, and, in the same area, Wolff et al. (2018) estimated an emission of 643 gC m^{-2} $year^{-1}$. The lower annual respiration at our site could be attributed to higher soil bulk
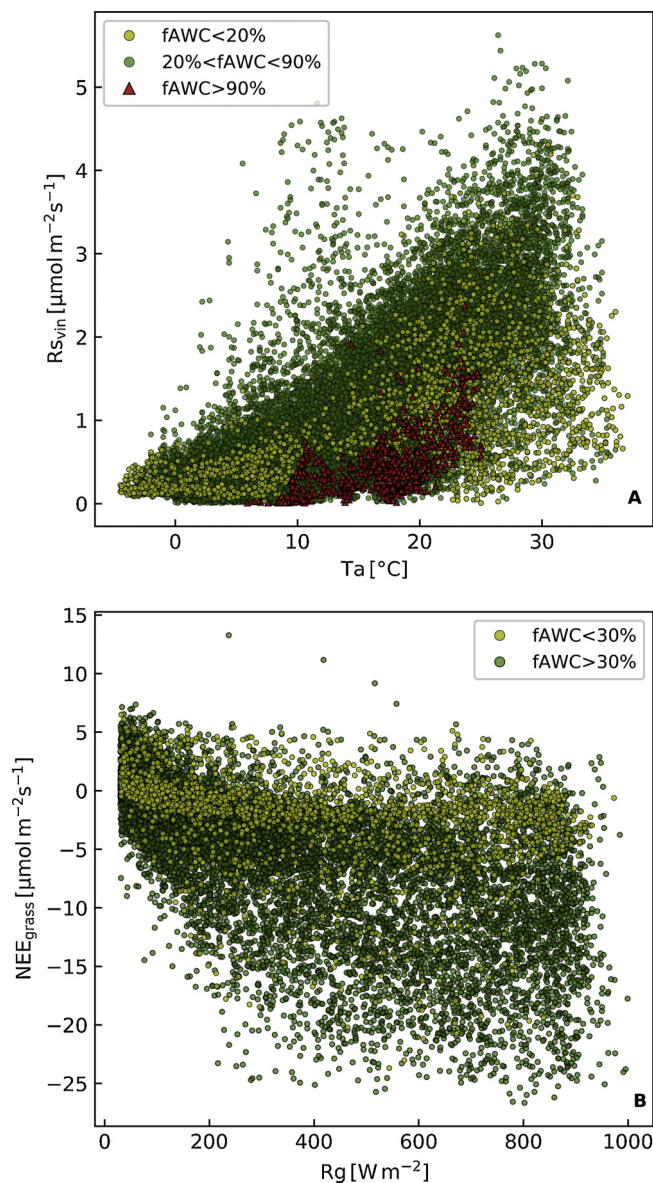
Fig. 4. a) Scatter plot of half hourly air temperature (*Ta*) and vineyard soil respiration (*Rs*$_{vin}$). Colors represent different fractions of soil available water content (*fAWC*): yellow dots *fAWC* below 20%, green dots *fAWC* between 20 and 90%, and red triangles *fAWC* above 90%. b) Scatter plot of half hourly global radiation (*Rg*) and grass net CO_2 flux (*NEE*$_{grass}$) at *fAWC* below (yellow dots) and above 30% (green dots). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

density and clay content, which can reduce soil respiration (Gaertig et al., 2002; Pengthamkeerati et al., 2006; Wang et al., 2003). Unexpectedly, the annual respiration rates of our and previously cited studies are inversely related to plant density, that is known to be positive related to root density (Archer and Strauss, 1985; Smart et al., 2006). Thus, differences in soil properties, management and climatic conditions seem to prevail over planting density in determining soil CO_2 efflux.

In natural ecosystems, where most studies on soil respiration have been conducted, soil C release in forests across the world ranges from 220 to 2560 gC m^{-2} year^{-1} (Wei et al., 2010). Compared to forest sites, our study is located in the low respiration range and this can be explained by several factors. Among them: lower SOC available for microbial respiration (Carlisle et al., 2006; Detwiler, 1986; Murty et al., 2002; Post and Kwon, 2000); higher soil compaction that increases

diffusive resistance to gas movement (Gaertig et al., 2002; Hashimoto and Suzuki, 2002; Pengthamkeerati et al., 2006); and lower standing vegetation density, resulting in less root biomass (Franck et al., 2011; Grossman and Dejong, 1994; Huang et al., 2005; Lakso et al., 1999; Smart et al., 2006).

3.3. Grass cover CO_2 fluxes

The net CO_2 exchange of the grass sward in the alley (*NEE*$_{grass}$), measured by the transparent chamber, generally followed global radiation pattern (Fig. 3d). In winter, daily fluxes were small and positive (CO_2 release) until March. Afterwards, the herbaceous vegetation resumed the activity and net daily fluxes became negative (CO_2 uptake), gradually increasing in magnitude until June. Nevertheless, in both summers, photosynthesis was depleted during cloudy days or dry conditions. Actually, when *fAWC* fell below 30%, daily net CO_2 fluxes were generally slightly negative or even positive (Fig. 4b), especially in July and August. The peak of daily CO_2 uptake was recorded in June 2015 (−6.2 gC m^{-2} day^{-1}), while the greatest release on a daily basis was in August 2016 (3.5 gC m^{-2} day^{-1}), during a dry period. On annual basis, the net C absorption by the grass sward was about −286 gC m^{-2} year^{-1} in 2015.

To our knowledge, no long-term measurements of net CO_2 exchange of inter-row cover crop in vineyards or orchards have been conducted so far. A study by Uliarte et al. (2013) used spot chamber measurements to compare CO_2 fluxes of different cover crop species. However, most of the investigations about cover crop C budget in vineyards investigated changes in soil C stock (Steenwerth and Belina, 2008; Wolff et al., 2018). On the other hand, several studies on CO_2 flux dynamics have been conducted on grassland ecosystems applying the eddy covariance technique. The net C exchange of grasslands has been shown to be quite variable among seasons and sites, ranging between 29 and −464 gC m^{-2} year^{-1} (Abdalla et al., 2013; Flanagan et al., 2002; Soussana et al., 2007; Xu and Baldocchi, 2004; Zeeman et al., 2010). This variability is caused primarily by different climate and soil characteristics but, for the same site, management effects seems to prevail (Ammann et al., 2007; Zeeman et al., 2010). The annual C budget of the grass cover measured at our vineyard lays around the middle of this range.

3.4. Disentangling carbon fluxes within the vineyard ecosystem

In order to clarify the role of the inter-row grass cover in the vineyard C budget, we compared vineyard net CO_2 flux (*NEE*$_{vin}$) measured by eddy covariance with ground net CO_2 flux (*NEE*$_{ground}$) monitored with soil chambers. *NEE*$_{ground}$ was calculated as the weighted average of bare soil respiration and net flux of grass sward, based on their fractional areas, which varied during the study period due to periodic cultivation of the alleys (Section 2.3). We estimated the potential ground net CO_2 flux if no tillage had been performed (*NEE*$_{groundNT}$), keeping *A*$_g$ at 100%.

Previous studies compared EC and soil chamber fluxes (Fox et al., 2008; Speckman et al., 2015; Wang et al., 2013, 2010), showing in some cases scarce agreement due to uncertainty arising from the comparison of techniques with different temporal and spatial scales (Barba et al., 2018; Riederer et al., 2014; Wang et al., 2017). Indeed, in our analysis, we should consider the intrinsic variability of the vineyard ground conditions in the EC footprint (few hectares on average) compared to the soil enclosed in the chamber collars. There could have been transient conditions when chamber representativeness was weakened by disturbances that could be detected by EC but not by the chambers. For example, in case of heavy rainfall, some spots in the vineyard could be flooded and others not. Chambers would be representative of only one of these conditions, while EC can detect the whole mosaic. Another source of disturbance could be related to heavy tractor traffic in the alleys for spraying or topping in spring and summer, damaging grass cover (especially after rains) and increasing soil compaction. This
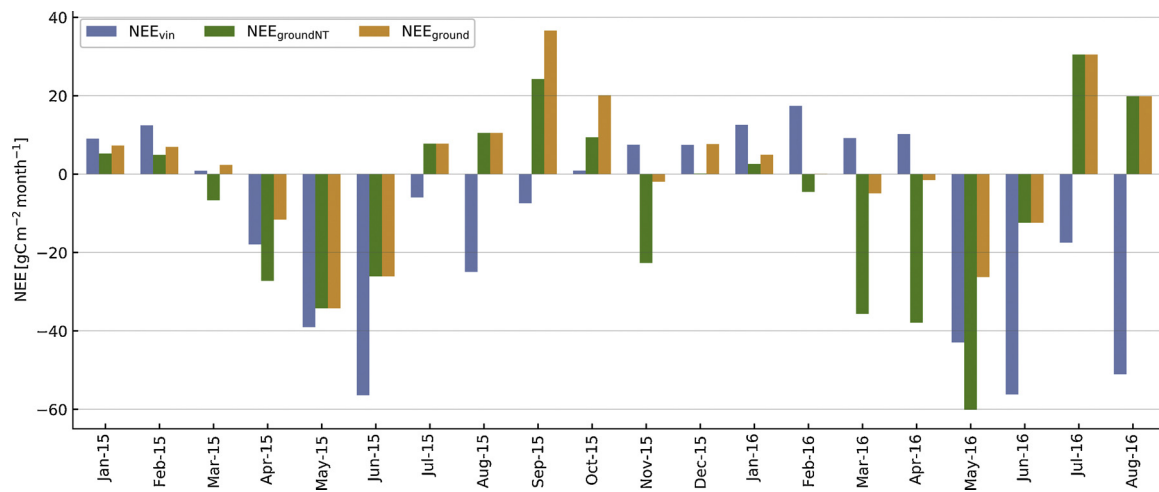
Fig. 5. Monthly integrals of net vineyard CO_2 exchange measured with eddy covariance (NEE_{vin}, blue), actual net ground CO_2 exchange derived from soil chamber measurements (NEE_{ground}, orange) and in the no-cultivation scenario ($NEE_{grounNT}$, green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

probably affected both herbaceous vegetation health and cover area, but also CO_2 emission from the soil, reducing the representativeness of ground fluxes measured by soil chambers. For instance, the net grass C uptake derived from clear chamber might have been higher compared to the actual uptake of grass sward in the EC footprint after tractor transit. At the same time, different soil characteristics, transient flooding or soil cracking could have decrease or increase soil respiration in EC footprint compared to chamber measurements. Nevertheless, these conditions were rare and limited to short periods and, despite the uncertainty raising from upscaling punctual measurements, the comparison of fluxes measured at different scales is still a valid option to disentangle ecosystem flux into its components (Brændholt et al., 2018).

In Fig. 5, monthly net CO_2 fluxes for vineyard and ground are reported. Ground fluxes were positive in winter and dry summer periods, whereas they became negative in spring and early summer, indicating a net uptake of CO_2 by this compartment. Ground fluxes showed to be affected by soil cultivation, exhibiting higher emission rate in winter and significantly lower uptake in spring, compared to the no-tillage scenario. Previous studies showed that the effect of tillage on CO_2 fluxes is temporary, increasing soil respiration only for a short period after operations, thus having low impact on yearly C budget (Almagro et al., 2017; Steenwerth et al., 2010; Wolff et al., 2018). Therefore, we could argue that the higher emission of CO_2 from tilled soil was primarily caused by reduction of herbaceous vegetation area, affecting its potential CO_2 uptake, rather than augmented soil respiration. For this reason, we chose to not perform tillage in inter-row bare soil collar in order to allow continuous and undisturbed monitoring. Considering that soil management was performed only three times during the study period, and the temporariness of its effects, we believe that non-tilled bare soil respiration (Rs_i) could represents fluxes of the tilled surface in the vineyard.

The impact of soil cultivation on ground carbon budget can be clearly observed in the pattern of cumulative fluxes (Fig. 6). The reduced uptake of CO_2 in November 2016 and higher emission in the following winter, resulted in an offset of about 90 gC m^{-2} between NEE_{ground} and $NEE_{groundNT}$ at the beginning of March 2016. Afterwards, the activity of herbaceous vegetation started to increase and the ground could have acted as an important sink of CO_2 until June. However, the actual uptake was strongly limited due to sward disruption by rotary tillage in April. Indeed, at the end of the study period, the net C budget of the vineyard floor was about $+40$ gC m^{-2}, although it could have been around -148 gC m^{-2} if no soil cultivation of the alleys had been performed.

The difference between NEE_{vin} and NEE_{ground} can be used to clarify the role of vines in the vineyard C budget, which can be either net CO_2 release or absorption. Vineyard and ground fluxes showed similar patterns in some periods, but they exhibited strong differences in others (Fig. 5). In winter, both fluxes were generally positive and NEE_{vin} was slightly larger, probably due to aboveground vine respiration and decomposition of pruning debris, not taken into account in soil chamber measurements. In March of 2015, the monthly totals of ecosystem and ground fluxes were very similar and close to zero, indicating an overall balance between photosynthesis and respiration. This confirms our expectation that vine and ground fluxes should be similar in winter and spring, since the contribution to ecosystem CO_2 exchange by vines is minimum because of dormancy. In April and May, fluxes were still comparable but larger in magnitude and with a negative sign. This indicates that the CO_2 uptake in spring was mainly by the herbaceous vegetation, that encountered favorable weather conditions to grow, earlier compared to grapevine. Grapevine bud break was in mid-April and the leaf area became significant towards the end of May, reaching full development at the end of June. Indeed, in June, the difference between ground and ecosystem fluxes became considerable, with NEE_{vin} being more than double NEE_{ground}. The latter was smaller compared to the previous month, probably because vines were shadowing grass in the alleys during most of the day. The activity of both vine and herbaceous vegetation was strongly reduced in July due to high air temperatures and low soil moisture, as outlined before. However, vine seemed to be less affected by dry and hot conditions compared to grass. Indeed, monthly NEE_{vin} remained negative until September, even if the ground compartment was a source of CO_2 in that period. The high C release in September and October was likely due to soil cultivation carried out in September, and the grass floor recovered only in November, showing a little uptake. In October, the vine activity decayed, leaf fall started and plants gradually entered the dormancy period. The vineyard was a net source of CO_2 from October 2015 to April 2016, even if ground fluxes were slightly negative in November, March and April. The decomposition of vine leaves and pruning debris may be one of the reason for higher ecosystem respiration compared to ground during these months. From May to August 2016, the pattern was similar to the same months of the previous year, with a drop of ecosystem CO_2 uptake in July. However, water and heat stress seemed to be lower in this second summer, and grapevine recovered in August thanks to few rains. In summer 2016, better meteorological conditions than 2015 (i.e. more distributed precipitation and lower maximum temperature) lead to higher summer vineyard C absorption (-125 gC m^{-2} in summer 2016 compared to -87 gC m^{-2} of 2015). The
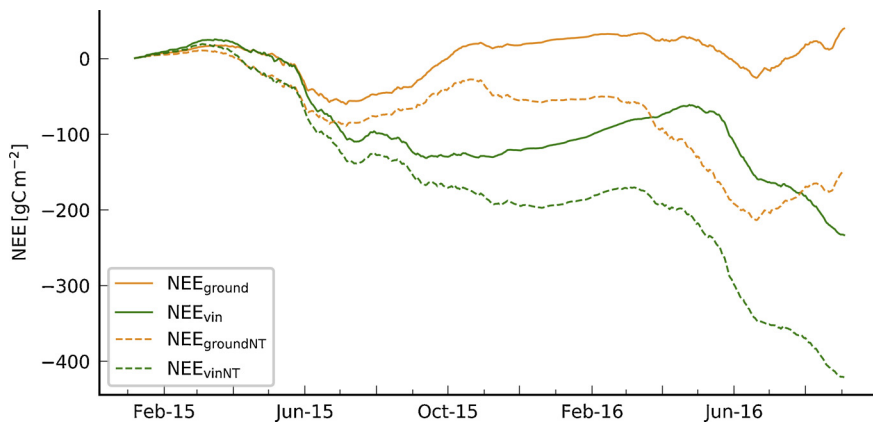
Fig. 6. Course of cumulated C fluxes of ground compartment and whole vineyard, considering soil management (NEE_{ground} solid orange line, NEE_{vin} solid green line) and no-cultivation scenario ($NEE_{groundNT}$ dashed orange line, NEE_{vinNT} dashed green line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

herbaceous vegetation, on the contrary, stopped to act as a C sink in July and did not recover, showing steady higher respiration fluxes compared to the previous year.

The ground compartment presented slightly negative or even positive C budget (-8 and $+38$ gC m^{-2} in summer 2015 and 2016 respectively), probably as a consequence of observed grass drying and soil cultivation. The low C uptake in 2015 was probably mainly related to dry soil conditions, while in 2016 soil tillage carried out in spring substantially increased CO_2 emission in the following months. These results suggest that the competition for water between grass cover and vines was low during summer stressing periods, as previously reported by Steenwerth et al. (2016). At our site, the herbaceous vegetation has a shallow root system (5–10 cm), while vine roots can explore greater depths (Archer and Strauss, 1985; Celette et al., 2008; Klodd et al., 2015; Wolff et al., 2018), using water stored in soil layers unreachable by grass. Nevertheless, in some cases competition between vine and cover crop has been reported, depending on vine age, kind of cover crop, soil and climatic conditions (Garcia et al., 2018). Indeed, Celette and Gary (2013) found that, in dry years, vines with permanent cover crop suffered more stress compared to vines with a temporary cover crop (not present in summer).

At the end of the study period (January 2015–August 2016), the net overall vineyard C uptake was about -233 gC m^{-2}. However, it could have been greater (-421 gC m^{-2}), if soil cultivation had been avoided. In 2015, NEE_{ground} was about 25 gC m^{-2} year^{-1}, while vineyard NEE -114 gC m^{-2} year^{-1}. Considering the no-tillage scenario, the C absorption by vineyard floor could have been about -55 gC m^{-2} year^{-1}, roughly 38% of the potential vineyard annual NEE. Similarly, Palese et al. (2013) estimated that spontaneous vegetation in a Mediterranean olive orchard sequestered about 35% of the total fixed CO_2, and Chamizo et al. (2017) measured a 50% contribution of grass cover NEE in another olive orchard. These findings indicate that cover crop or resident grass cover can have an important role on the yearly C budget of woody crops. Indeed, inter-row vegetation could act as a buffer for C uptake during the dormancy period of woody crops, especially in spring. However, it could eventually become a source of CO_2 during dry summer, as also outlined by Chamizo et al. (2017). Nevertheless, this natural decline of the cover crop during summer is strategic to minimize water competition with vines.

4. Conclusions

In this paper, we analyzed the long-term dynamics of the C budget of a vineyard in Northeast Italy, measuring CO_2 fluxes at ground and ecosystem levels with the aim of disentangling the C budget throughout almost two years of continuous monitoring. We demonstrated the effects of soil management on vineyard C balance, showing that inter-row grass cover can play a remarkable role in CO_2 annual ecosystem uptake. The resident herbaceous cover was subjected to heavy water stress in

summer, that caused strong reduction of its activity. This behavior is important to reduce water competition with grapevine during dry periods. Indeed, especially in dry climates, it is fundamental to prefer summer-dormant cover crops to maximize C absorption without compromising water availability to grapevine. In this way, green cover can positively coexist with vines, providing ecosystem services during the rest of the year (e.g. CO_2 uptake, augmented rain infiltration, soil erosion reduction, and SOC increase (Garcia et al., 2018)). Our measurements revealed that soil management had a considerable influence on vineyard C balance, affecting the temporal and spatial continuity of the herbaceous cover. Indeed, in our case, the net C uptake of the vineyard was about 45% less compared to the no-tillage scenario. Our study demonstrates that, avoiding periodical tillage, the uptake by vineyard grassed floor (-55 gC m^{-2} year^{-1}) could almost reach the "4 per mille" goal of 60 gC m^{-2} year^{-1} to compensate global anthropogenic C emissions (Minasny et al., 2017). Hence, conservative practices (e.g. green cover and minimum soil disturbance) are desirable to improve viticulture sustainability, increasing CO_2 uptake and, at the same time, reducing CO_2 emission.

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