Carbon Footprint assessment on a mature vineyard

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Abstract

It is recognized that agriculture is the fourth largest contributor to global greenhouse gases (GHGs) emissions by sector (14%) and the wine industry is one of the most important economic sectors in terms of production and distribution worldwide. However, agriculture can also contribute to sequester carbon, so it is important to understand the double role of such systems.

Even if the agricultural phase is recognized by several authors to have a strong environmental impact during the wine production, only a few studies estimate GHG emissions related to this stage. In addition, the determination of the Carbon Footprint (CF) (i. e. the amount of direct and indirect CO_2 emissions caused by a production process) of the agricultural phase is not a simple task due to the large uncertainty related to local characteristics, climate, land, agricultural practices, grape type, and to a general lack of experimental data.

The main goal of this work was to determine the CF of a mature vineyard during the grape production process. The CF analysis was conducted in a typical Mediterranean vineyard located in the South of Sardinia (Italy) using 1 kg of grape yield as functional unit. The system boundary was "from cradle to gate" excluding winemaking processes, distribution, and consumption. In addition, the study was addressed to assess the role of the vineyard to offset carbon emissions at the end of the productive year. The Eddy Covariance technique was used to directly measure the CO_2 exchange over the vineyard and the net CO_2 budget was computed by combining the measured fluxes and the GHG emissions estimated by the CF analysis.

Results showed that the production of one kg of grape determined a total amount of GHG emissions of 0.39 kg CO_2-eq and most of them derived from external inputs such as fossil fuel combustion and soil management.

In addition, ecophysiological processes could contribute to offset the CO_2 emissions released during the agronomic practices.

Keywords:
Carbon balance; Agricultural phase; Grape; Eddy Covariance; GHG emissions; Vineyard management

1 Introduction

In recent years, there has been a growing concern related to the eco-sustainability of production processes, and consumers are becoming more interested in environmentally friendly practices, products, and services. The widespread adoption of intensive production systems in agriculture leads to increase soil degradation, loss of biodiversity, reduction in soil organic matter and water, and increase in air and soil pollution (Zabini, 2008). Measures are then needed to promote sustainable production processes.

The fourth largest contribution to global greenhouse gases (GHGs) emissions is given by agriculture (14%) (Metz et al., 2007), and the wine industry is one of the most important economic sectors in terms of production and distribution worldwide. The International Organisation of Vine and Wine (OIV) states that, in 2014, 270 million hectoliters of wine have been produced on a total vineyard area of more than 7.5 million hectares. The major producing Countries in the Mediterranean Basin (Italy, France, and Spain) reached a total area of approximately 2.6 million hectares and a production of almost 130 million hectoliters (OIV, 2015). The noteworthy economic impact of these data makes necessary the development of methodologies aiming to estimate greenhouse gases (GHGs) emitted in the atmosphere from everyday products and services, and to search for useful strategies to reduce them.

Life Cycle Thinking (LCT) is a quantitative approach which aims at taking into account all life cycle phases of a product (e.g. extraction of the raw materials, pre-production processes, production, consumption, end-of-life) in a broad range of methodologies and instruments for sustainability assessment and management. Several LCT-based methods have already been produced so far, and the Life Cycle Assessment (LCA) is one of the most known to account for the environmental burdens associated with the different life cycle stages of wine (Petti et al., 2010; Neto et al., 2013; Vázquez-Rowe et al., 2013), and providing multiple impact categories to be analyzed (e.g. global warming, human and environmental toxicity, natural resource depletion, ozone layer depletion, summer smog) However, LCA also presents disadvantages due to its holistic and comprehensive principles. Consequently, LCA studies developed a number of indicators, such as water footprint or carbon footprint (CF) (Čuček et al., 2012; Laurent et al., 2012; Scipioni et al., 2012).

CF analysis, as a part of the LCA approach, quantifies CO_2 emissions directly and indirectly caused by an activity or accumulated during the lifecycle of a product or service (Wiedmann and Minks, 2007). This approach enables to identify the contribution of a production process to climate change considering emissions of the GHGs covered by the Kyoto Protocol (Bosco et al., 2011). It is typically expressed in kg CO_2-equivalent (CO_2-eq), i.e. a measure of the greenhouse effect of a gas considering its Global Warming Potential (GWP).

Recently, several approaches and guidelines have been developed for accounting GHG emissions, including (1) methodologies at territorial scale developed by the IPCC, (2) the Publicly Available Specification 2050 (PAS 2050) developed by the British Standard Institute and the Carbon Trust (BSI, 2011), and the (3) Greenhouse Gas Protocol (GHG-Protocol) developed by the World Resources Institute and the World Business Council for Sustainable Development (WBCSD/WRI).

In the wine sector, the most used protocols are the International Wine Carbon Protocol (IWCP), the French Bilan Carbone (ADEME, 2010), and the OIV-GreenHouse Gas Accounting Protocol (OIV-GHGAP).

Winemaking process can be subdivided into two main phases: agricultural and industrial. Agricultural phase accounts for GHG emissions related to practices for vineyard planting, pre-production and grape production sub-phases, while the industrial phase includes vinification, bottling, packaging, distribution, and waste management processes (Bosco et al., 2011).

Several studies applied the LCA methodology to evaluate the environmental performance of the wine sector (Notarnicola et al., 2003; Aranda et al., 2005; Ardente et al., 2006; Petti et al. 2006; Pizzigallo et al., 2008; Gazulla et al., 2010; Point et al., 2012; Vázquez-Rowe et al., 2012a,b; Benedetto 2013; Neto et al., 2013), and the CF analysis (Colman and Paster 2007; Smyth and Russell 2009; Cholette and Venkat 2009; CSWA 2009; Smart et al., 2009; Bosco et al., 2011; Pattara et al., 2012; Rugani et al., 2013; Vázquez-Rowe et al., 2013). However, only a few studies analyzed the CF for a single stage of the production process by addressing specific aspects related to it as, for example, the agricultural phase (Kavargiris et al, 2009; Venkat, 2012), the wine

distribution and the end-of-life (Cholette and Venkat, 2009; Reich-Weiser et al., 2010).
In the winemaking process, the agricultural phase has been recognized to contribute from 17% (Rugani et al., 2013) up to 40% (Benedetto, 2013; Neto et al., 2013) to GHG emissions. Studies reported that the use of pesticides, fertilizers, and diesel consumption for vineyard practices are the main sources of GHG emissions in the wine chain (Niccolucci et al., 2008; Pizzigallo et al., 2008; Bosco et al., 2011; Point et al., 2012; Benedetto 2013; Rugani et al., 2013; Fusi et al., 2014).
However, the determination of the CF in the agricultural phase is not a simple task because of various issues. Large uncertainty in the estimation derives from differences in the local ecosystems, climate conditions, land texture, agricultural practices, and grape varieties (Rugani et al., 2013). In addition, a general lack of experimental data and information makes difficult the CF quantification of this stage.
Apart from the production system complexity, a critical point is to include, in the net carbon budget estimation, the carbon sequestered by the different components (soil and grass cover, woody biomass, etc.) of the vineyard system (OIV, 2011) that can offset the emissions from fossil fuel, usually representing the larger source of GHG in the agricultural systems. Most of studies assume balance between the biogenic CO_2 sequestered and released back to the atmosphere. As a result, CF analysis usually omits biogenic carbon issues. In addition, studies are largely based on carbon estimates and only part of them uses experimental data.
Micrometeorological methods are commonly applied to directly measure CO_2 exchanges between a system and the lower atmosphere, and the Eddy Covariance (EC) technique is the standard methodology used in the Fluxnet International Monitoring Network (Baldocchi, 2003). It is commonly used to obtain long-term measurements of CO_2 exchanges and helps in understanding and quantifying ecosystems capacity to absorb atmospheric carbon.
Even if the EC method is widely used over different ecosystems around the globe, so far little is known about the vineyard ability to sequester carbon and offset GHG emissions. CO_2 flux measurements over vineyards were usually reported for short measurement periods (a few weeks up to one month) (Spano et al., 2004; 2008), apart the three-year period analyzed by Guo et al. (2014).
The general aim of this work was to investigate the vineyard capability to offset GHG emitted during the agricultural phase of the production process. In addition, the research tried to identify the agronomic practices that mainly contributed to emissions, affecting the global carbon budget, and to include the biogenic contribution (quantified through direct measurements) in the calculation of the net carbon budget . The analysis was conducted in a typical Mediterranean vineyard. The IWCP Protocol was used to perform the CF analysis, while an Eddy Covariance tower was set up over the studied vineyard to directly measure the CO_2 flux in the soil-vegetation-atmosphere continuum.

2 Materials and Methods

2.1 Carbon Footprint methodology

The CF analysis was carried out in an experimental site located in the South of Sardinia (Italy). It was performed using one kg of grape yield as functional unit, and identifying a system boundary "from cradle to gate", excluding winemaking processes, distribution, and consumption. The analysis focused on the main agricultural practices conducted in the period October 2009-September 2010: fertilization application, soil management tillage, pruning, and harvesting.

The CF was computed following the International Wine Carbon Protocol (IWCP), and adopting its related calculator named International Wine Carbon Calculator (IWCC). In this work, only emissions related to Scope 1 or "primary footprint" (i.e. all emissions under the direct control of the farm) were considered and limited to the agricultural phase. Specifically, these are emissions related to the use of fossil fuel, both for agronomic practices and for travelling from the farm center to the field, and emissions from activities affecting the short-term carbon cycle (e.g. pruning, harvesting, and human metabolism of workers). All GHG emissions are expressed as CO_2 amount (kg) when carbon was directly released by the analyzed process or as CO_2-eq (kg) when Nitrogen (N) emissions were included, as requested by the CF guidelines.

Emissions from stationary fuel use (water heaters and frost fighting equipment), and fugitive emissions are not considered since heaters or boilers are not used in the investigated farm. Also, emissions from waste disposal are omitted because the amount is not significantly relevant as well as emissions due to energy consumption for water application, which is produced outside the farm boundaries.

Vineyard management information (energy and material inputs) related to the agricultural phase are reported in Table 1.

2.1.1 Calculation methodology

The analysis was performed through the IWCC. However, since the use of this calculator seems to overestimate the CF calculated with other LCA softwares (Rugani et al., 2013), GHG emissions related to some terms were calculated using data directly collected by the authors through specific questionnaire and interviews with the farm owners (Table 1).

Direct CO_2 emissions related to fossil fuel (diesel) consumed for agronomic practices were calculated based on the fuel quantity method of the IWCC by using an emission factor of 74.01 kg CO_2 GJ^{-1}. Fuel consumption due to travels was calculated considering the IWCC travel distance method. Travel distance was 6 km per round-trip for a total of 18 times per year (i.e. 108 km y^{-1}).

An emission factor of 2.745 kg CO_2 l^{-1} diesel (IWCP) was used to estimate carbon emissions due to travels.

In the experimental site, organic and chemical fertilizers, with a N content of 2% and 9%, respectively, were used. A default value of 0.01 was used to estimate N emissions per each fertilizer, while emissions from managed soil were estimated using a factor of 3, following the IWCP. Differences in land cover and soil composition are not considered in this calculation.

Pesticide emissions were not calculated since a few amount (4-7 kg ha^{-1}) of a Sulphur compound is applied per year, and it was considered negligible (Fusi et al., 2014).

Crop residues after pruning are usually cut and incorporated into the soil. A sample of crop residues was collected and desiccated to estimate an amount of 1289.2 kg CO_2 ha^{-1}, which is considered totally released into the atmosphere during the year. The N content (% N kg^{-1} dry matter) in crop residues was estimated using the emission factor (0.25) suggested by Alfano et al. (2011) and then converted in CO_2-eq emissions using the 310 Global Warming Potential factor (100 years time horizon) (IPCC, 1995).

Carbon dioxide emissions related to grape production were calculated in a different way for grape juice and grapefruit components (grape skin, stalks, and grape seeds). Brix degrees (Table 1) were used to calculate the CO_2 content in the grape juice. A moisture content of 80% on fresh weight (established as mean value from lab analysis) was used to calculate the CO_2 stored in grapefruit components, while a value of 2.06% (Baraldi et al., 2010) was used to estimate the N content.

The contribution of human labor to climate change is not usually included in LCA and CF analysis, even if this phenomenon is strictly related to anthropogenic activities, especially for viticulture (Rugani et al., 2013). Human labor consumes resources and releases emissions. In line with Rugani et al. (2012), an emission factor of 0.46 kg CO_2 h^{-1} was used to estimate total emissions from human respiration (http://www.engineeringtoolbox.com/co2-persons-d_691.html).

2.2 Micrometeorological measurements

The Eddy Covariance (EC) technique was used to directly measure the exchanges of energy and mass (carbon and water) between the vineyard and the atmosphere. The EC system was set up in June 2009 at 2.8 m above the ground. It consisted of an IRGA Li-7500 open-path gas infrared analyzer (Li-Cor Biosciences, Lincoln, NE, USA), a CSAT3 three-dimensional sonic anemometer (Campbell Scientific Inc. (CSI), Logan, UT, USA), and a CR5000 datalogger (CSI). Solar panels supplied energy to the tower.

Eddy Covariance data were acquired at 10 Hz and averaged every 30 minutes. Raw data were processed using the EddyPro v. 4.2.1 software developed by Li-Cor Biosciences. The amount of data removed by quality check was 18% over the period (October 2009-September 2010).
Net ecosystem exchange (NEE) is the net CO_2 exchange with the atmosphere directly measured with the EC technique. Positive NEE values represent net carbon (C) emissions to the atmosphere and negative values represent the C amount sequestered from the atmosphere, according to the atmospheric science convention.
Ecosystem emissions due to respiration processes (Reco), as well as Gross Primary Productivity (GPP) were estimated with the marginal distribution sampling method (MDS) (Reichstein et al., 2005), implemented in http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/ (2013 version). The online tool was also used to fill gaps in the dataset.
Four heat flux plates (mod. HFP01SC, Hukseflux, Delft, NL) were located, along a transect between rows, at -0.07 m soil depth to have a representative measure of soil heat flux (G). Soil temperature changes in the soil layer above -0.07 m were measured to correct G for heat storage.
Meteorological and radiometric stations were also placed in the site to measure the main meteorological variables and the radiation balance components, respectively. Air temperature (Tair, °C), relative humidity (RH, %), precipitation (Pcp, mm), photosynthetically active radiation (PAR, μmol quanta m^{-2} s^{-1}), and incoming and outcoming solar radiation (W m^{-2}) were measured. During the growing period, the Leaf Area Index (LAI) was also monitored by LAI-2000 (Li-cor, Lincoln, NE, USA) based on the principle of interception of the light radiation from vegetation. In addition, soil temperature and moisture were monitored at -0.20, -0.40, and -0.60 m depths in several vineyard locations.
The energy balance closure was used to evaluate the accuracy of measured data. In the literature, deviations of about 20-30% from closure are commonly observed in surface energy budget measurements (Twine et al., 2000; Wilson et al., 2002). The observed energy balance closure was in line with those reported in the literature (slope = 0.76; R^2 = 0.86), so the measurements accuracy was considered acceptable.

2.3 Experimental site

The study was conducted in a typical Mediterranean vineyard located in the South of Sardinia, Italy (39°21'43" N, 9°07'26" E, 112 m asl). The 8-hectares vineyard was planted in 2000. The grapevine variety is Vermentino, which is trained in a Guyot system. The rows are oriented in east-west direction with 0.8 m between plants and 2.1 m between rows (5952 vines ha^{-1}). Vegetation is about

2.0 m tall with 50% ground shading of the clay soil. The vineyard is irrigated during the dry season through a drip system. Leaf Area Index (LAI) in the period May-September varied from 1.2 to 3.2.

3 Results and Discussion

3.1 Environmental conditions in the experimental site

Climate is typical of the Mediterranean area, with a mean annual temperature of 16.9 °C and mean annual precipitation of 484 mm. Annual precipitation measured at the site was 518 mm, mainly concentrated in spring and fall (Fig. 1a). Soil volumetric water content (SWC) ranged from 19% to 30% during the year, with an average soil moisture value of about 25% (Fig. 1a). Mean annual temperature was 15.5 °C, slightly lower than climate mean. Daily mean temperature ranged from 1.6 °C to 28.2 °C (Fig. 1b), with a minimum absolute value occurred in February 2010 (-1.2 °C) and a maximum in August 2010 (37.2 °C).

3.2 Carbon footprint analysis

Direct and indirect CO_2 (i.e. N converted into CO_2-eq) emissions were quantified per each agronomic practice and results are reported in Table 2.

Human induced emissions related to external inputs (fuel consumption, human work, fertilization application) and emissions due to soil management totaled 0.26 kg CO_2-eq kg^{-1}. The main processes affecting the global carbon budget, expressed in terms of GWP impact during the grape production phase, were represented by diesel consumption (both for field practices and travels), with 0.12 kg CO_2 kg^{-1}, and N released by the managed soil (0.13 kg CO_2-eq kg^{-1}). These two inputs are responsible for more than 90% to the total GHG emissions (Fig. 2). On average, diesel consumption covered 44% of the GWP impact, while emissions from managed soil accounted for 50%.

This analysis showed that fossil fuels and soil tillaging are the two main emission sources, but having a different impact on the global carbon budget. Soil tillaging affects the N emissions and the organic carbon stored into the soil (i.e. roots, pruning, litter residues), characterized by a relatively fast turnover (it is assumed that woody debris are respired away in about a year). On the other hand, fuel affects the global carbon reservoirs representing an additional source of CO_2 emissions. Similar results were found by other authors (Benedetto 2013; Fusi et al., 2014; Neto et al., 2013; Point et al., 2012; Venkat, 2012), while lower contribution for diesel consumption (20%) and N emissions from soil management (20-30%) was observed by Bosco et al. (2011) in Tuscany (Italy). Most of studies in the literature, however, agreed that the amount of consumed diesel and N content should be revised to guarantee a net improvement in environmental impacts reduction (Neto et al., 2013; Vázquez-Rowe et al., 2012b).

The impact of fertilization application is lower than the two previous inputs, contributing for about 5% (0.01 kg CO_2-eq kg^{-1}) to the global C budget. This value is in line with what reported in Spain (7%) by Vázquez-Rowe et al. (2012a) but lower than values reported by Bosco et al. (2011) and Point et al. (2012). However, differences in local climate conditions, grape variety, soil characteristics, and agricultural practices could explain the variability observed in the results from different studies (Rugani et al., 2013). Human work only contributed for about 2% to the global carbon budget (Fig. 2).

When considering emissions from both external inputs and biogenic components due to agronomic practices (i.e. crop residues), results from this study showed a total amount of GHG emissions of 0.39 kg CO_2-eq kg^{-1}. Both emissions from fossil fuel and crop residues decomposition contributed for about 30%, even if the crop residues release carbon that was recently fixed, so having no direct influence on the global carbon budget.

Our results are in line with other studies that analyzed emissions during the grape production phase. CO_2-eq emissions ranging from 0.20 to 0.67 per kg of grape yield were found by Venkat (2012) and Vázquez-Rowe et al., (2012b). Other studies refer the CF results to the 0.75 l wine bottle as functional unit, which corresponds to 1.1 kg of grape product. They found values around 0.30 (Bosco et al., 2011), 0.50 (Gazulla et al., 2010) and 0.80 kg CO_2-eq (Point et al., 2012) during the agricultural phase. It should be noted that, in each study, differences in vineyard management and grape yield, CF methodologies applied and external inputs considered concur to determine the differences in the final results, but all contribute to understand the role played by vineyards in releasing GHG emissions.

In the next paragraphs, the vineyard capability to offset the external emissions (in particular those due to fossil fuel), through its ecophysiological activity, is evaluated.

3.3 Micrometeorological measurements

This work represents one of the few studies reporting carbon fluxes measured over a vineyard during a long measurement period (one year). The Net Ecosystem Exchange (NEE) measured by the Eddy Covariance tower accounts for C sequestered by plants (in leaves, wood, fruit, and roots) (i.e. E, Table 2) and soil, as well as the C released by the fast decomposition of plant components after pruning (D), and from soil respiration. In addition, carbon from fuel combustion for field practices (A) and human work (C) (Table 2) should be considered even if, due to the general assumptions of the EC technique, the exact quantification of A and C emissions accounted in the measured fluxes is challenging.

The average Net Ecosystem Exchange (NEE) measured by the Eddy Covariance at the experimental site was -0.53 g C m^{-2} day^{-1}. The maximum daily carbon sequestration occurred on 25 July 2010 (-5.58 g C m^{-2} day^{-1}), while the maximum C loss was registered on 22 April 2010 (5.07 g C m^{-2} day^{-1}), mainly due to soil tillage practices. Data related to the carbon budget at monthly scale are presented in Fig. 3.

Results reveal that the vineyard was a net carbon *sink* during the growing period (May-September), when green vegetation is present, with maximum monthly NEE values in July and August (-100 g C m^{-2} and -108 g C m^{-2}, respectively), while C emissions (Reco) ranged from 76 g C m^{-2} (September) to 134 g C m^{-2} (June) (Table 3).

Row cropping clearly decreased the release of carbon when plant leaves were missing. Low values of carbon emissions are, in fact, observed in January 2010 and October 2009 (Table 3). In addition, soil tillage practices have a direct effect on increasing soil carbon release, resulting in carbon peaks emissions in March and April 2010 (Fig. 3, Table 3).

At annual scale, the vineyard was able to sequester 195 g C m^{-2}. This amount is lower if compared to other vineyard ecosystems, e.g. 868 g C m^{-2} y^{-1} as reported by Guo et al. (2014), or forest sites (Valentini et al., 1996). Compared to other agricultural ecosystems our values are lower (Hollinger et al., 2005; Schmidt et al., 2012), similar (Matthias et al., 2012; Mudge et al., 2011) or even higher (Zenone et al., 2013), showing that the vineyard could play a role in sequestering C. In terms of CO_2, our vineyard was able to annually sequester 715.05 g CO_2 m^{-2}.

The measured NEE showed large variability along the year, mainly attributed to the environmental conditions during the growing period. Air temperature and water availability (both due to irrigation and precipitation) are the main factors affecting C uptake (data not shown). In dry climates, as in the Mediterranean area, water resources are limited, especially during summer. Our measurements showed that when water is not a limiting factor (due to irrigation practices), carbon sequestration in the vineyard can reach relatively high values (June, July, and August, Table 3), as also found by Guo et al. (2014) in a semiarid vineyard in China.

3.4 Combined analysis for the net carbon budget calculation

As observed by other authors (Soosay et al., 2012), agricultural phase may contribute up to 28% of carbon emissions due to the biogenic components (i.e. decomposing biomass, timber decay) and carbon sequestration linked to vine growth and sugar production in the grapes. Since the difficulty to have reliable measurements or estimates of these quantities (Bosco et al., 2011), most of the studies assume that the amount of biogenic CO_2 sequestered from the atmosphere during vine and grape growth is equal to the amount of CO_2 released back to the atmosphere by the oxidation processes in pruning wastes and grapes (Neto et al., 2013) or they did not account for short-term processes (Pattara et al., 2012). As a result, CF analysis usually omits biogenic carbon issues, even if they have been taken up by CF guidelines (i.e. PAS 2050).

Our study tried to include both biogenic carbon sequestration and release into the CF calculation. The final carbon budget of the vineyard is then calculated taking into accounts all these terms by combining the NEE measurements and the CF calculated emissions.

First of all, the net biomass accumulated by the vineyard during the productive year was quantified. The biogenic carbon sequestered by grape yield (E) is considered completely respired away along the year, so this amount was removed from NEE to calculate the net biomass sequestration (Biom) of the mature vineyard:

$$Biom = NEE - E \qquad (kg\ CO_2\ kg^{-1}) \qquad (1)$$

and results showed an annual carbon sequestration equal to 0.24 kg CO_2 kg^{-1}. In terms of biomass, this amount corresponds to about 0.12 kg of dry matter per plant. This quantity represents the annual plant growth observed during the year, and highlights that the amount of CO_2 sequestered and released in the short-term processes is not balanced and it should be taken into account in the final carbon budget calculation.

In this context, the final carbon cost (CC) of the grape production process was calculated as the difference between NEE and the emissions by both biogenic components (indirect CO_2) and external inputs. It is needed to remind that turbulent flux (NEE) is strictly linked to the wind direction, wind intensity, and other conditions that may occur in the field. So, it is hard to relate the measured NEE with CO_2 emitted from external inputs, such as the fossil fuel (A) and human work (C). If the terms A and C are assumed to be completely missed by the EC measurements, the final carbon cost (CC) is calculated by adding these terms to the other emission sources as:

$$CC = -NEE + A + B + C + E + F + G + H + I \qquad kg\ CO_2\text{-eq}\ kg^{-1} \qquad (2)$$

The agricultural phase is then characterized by a net carbon release of 0.036 kg CO_2-eq per kg of grape. However, it is reasonable to also assume that the EC tower is able to include A and C emissions in the measured flux. In this case, the vineyard is able to offset GHG emissions due to the external inputs by sequestering 0.124 kg CO_2-eq kg^{-1}.

4 Conclusions

The Carbon Footprint analysis was conducted in a mature vineyard located in the South of Sardinia (Italy), and coupled with direct measurements of CO_2 fluxes through the Eddy Covariance technique, with the aim to quantify the global warming impact of the agricultural phase during a productive year.

This research represents an advancement in knowledge since a few studies focused only on the agricultural phase of the wine making process, and it represents the first attempt to relate GHG emissions of the grape production process to the effective capacity of the vineyard system to offset them in the field.

The Carbon Footprint analysis allowed to quantify the GHG emissions related to agronomic practices and results showed that emissions both from external inputs and biogenic components amounted to 0.39 kg CO_2-eq per kg of grape yield. In addition, the main terms responsible for CO_2 emissions in the atmosphere are external inputs (such as the fossil fuel combustion) and soil tillage. These results are in accordance with findings in the literature. Since farmer already reduced the amount of applied fertilizers, this practice does not have a relevant impact in the total GHG emission quantification. The conversion from the current conventional management to organic one will not probably determine a significant improvement. A solution to reduce the global warming impact resulting from the use of agricultural machinery could be found in reducing soil tillage practices and using biodiesel fuel (Benedetto 2013).

Plants physiological processes, row cropping, and soil contributed to sequester part of the carbon released during the year. Carbon exchanges measured by Eddy Covariance (NEE) revealed that the vineyard was able to accumulate, at annual scale, 0.7151 kg CO_2 per kg of grape yield. Further, the plants were able to grow of about 0.12 kg of dry matter per plant.

The net carbon balance calculated by coupling the CF results with the measured carbon exchanges, also pointed out that the vineyard was able to offset the CO_2 emissions released during the agronomic practices, depending on the amount of external inputs emissions accounted by the EC tower. The agricultural phase of the wine production process was, in fact, responsible for about 0.036 kg CO_2-eq emissions per kg of grape yield, but this trend could be opposite (i.e. the vineyard could sequester 0.124 kg CO_2-eq kg^{-1}) depending on the fraction of fuel and human respiration emissions included into the Eddy Covariance measured NEE.

Next steps of this research study will consist in including the other stages of the production process (wine making and distribution) in the carbon footprint analysis for determining their potential environmental implications.

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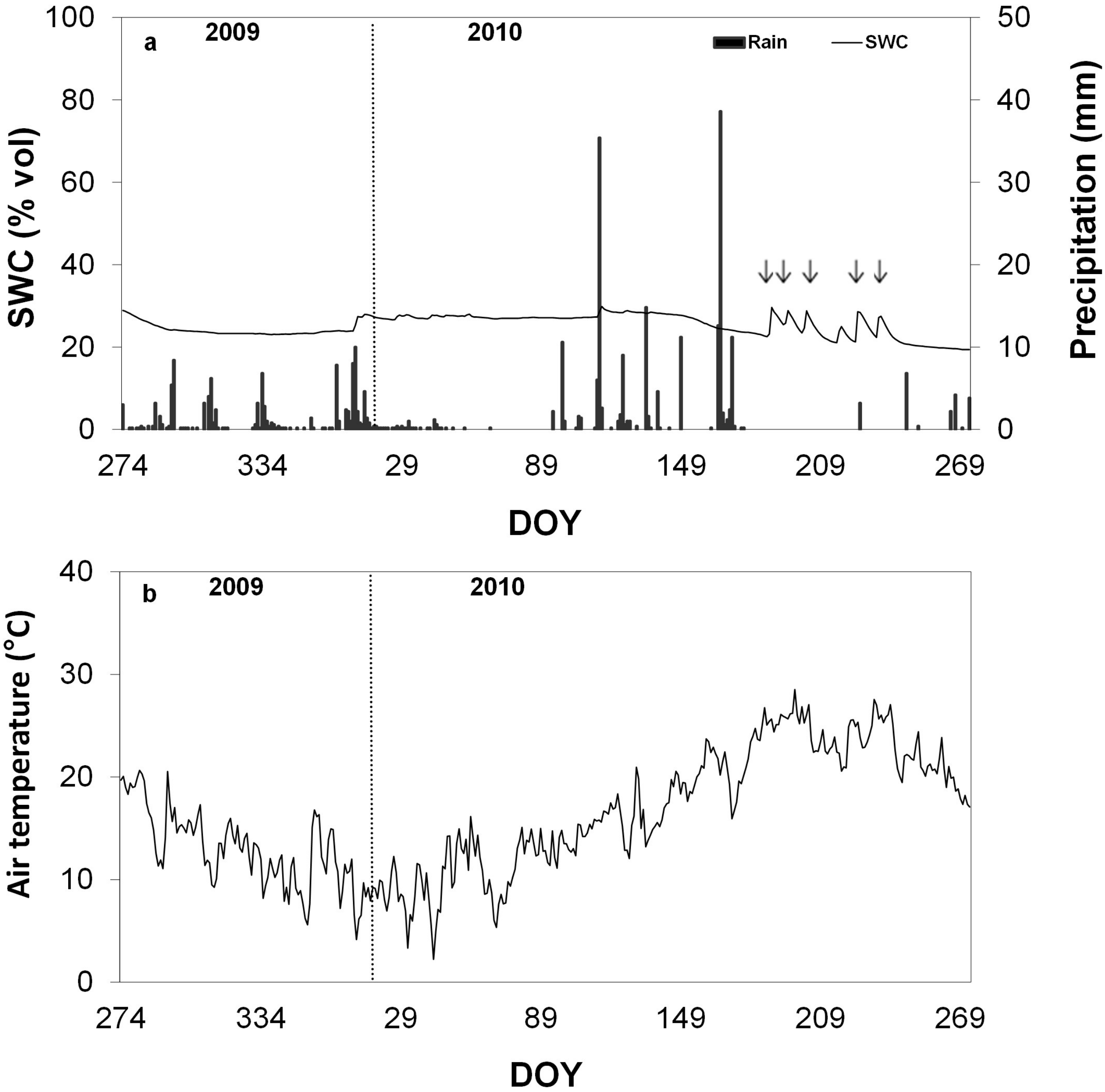

Fig. 1. Variation in daily precipitation (mm), volumetric soil water content (SWC) (average between measurements at -0.20 and -0.40 m) (a), and air temperature (°C) (b) in the experimental site from October 2009 to September 2010. Arrows in the upper plot indicate irrigation.

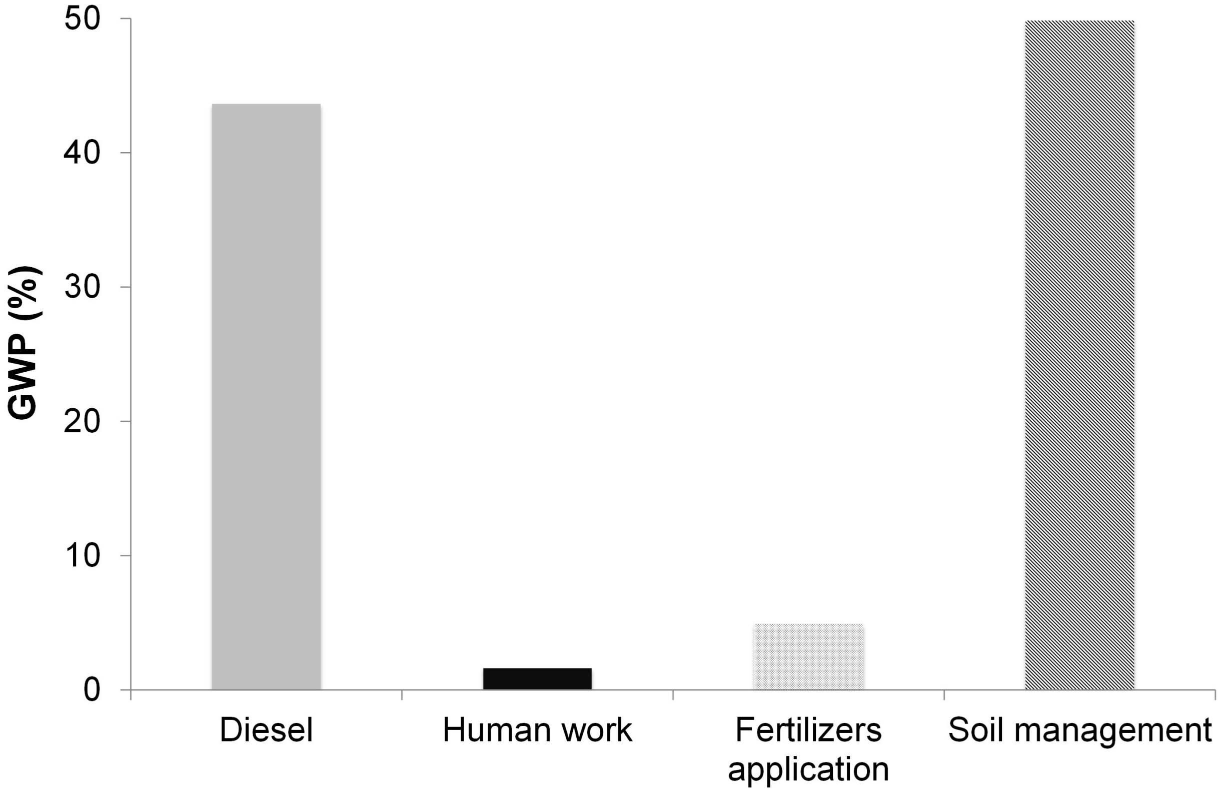

Fig. 2. Global Warming Potential (GWP) impact (kg CO_2-eq kg^{-1} of grape yield, expressed in % unit) during the grape production phase.

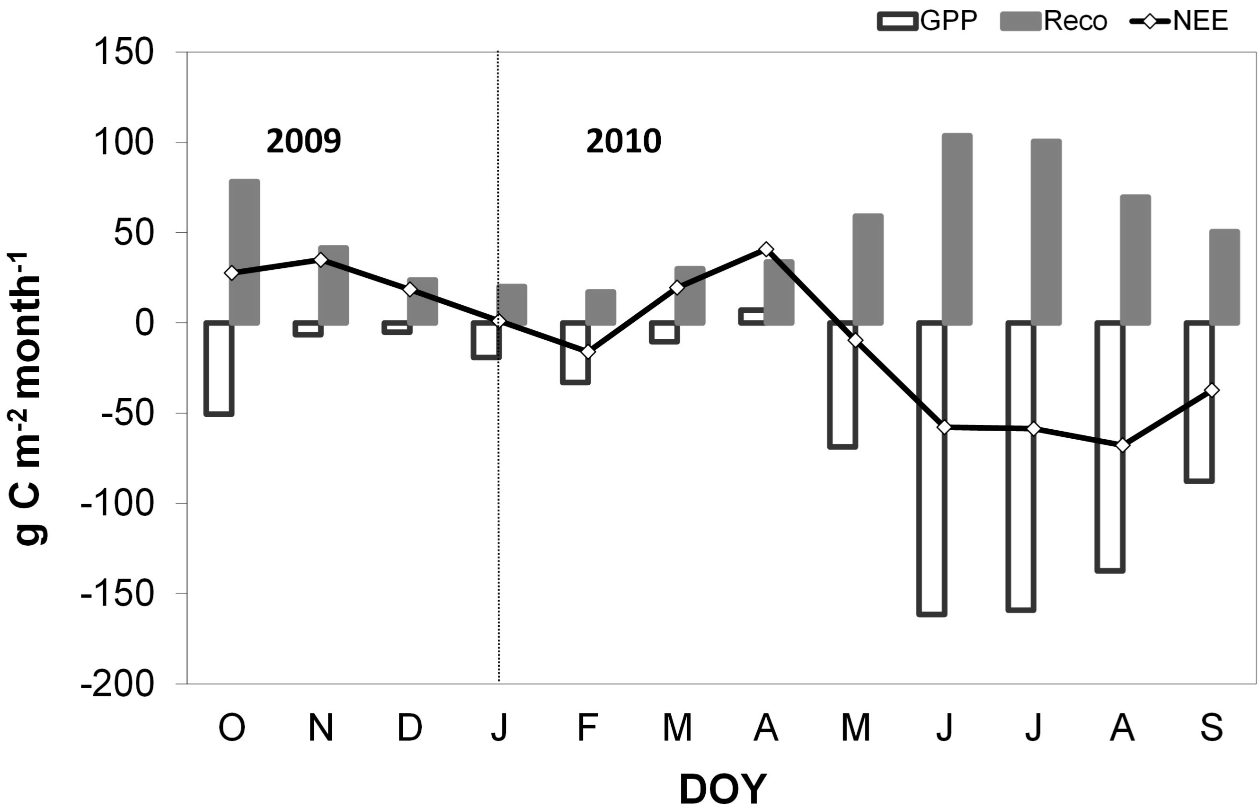

Fig. 3. Monthly variation in measured carbon fluxes (g C m^{-2} $month^{-1}$). GPP = Gross Primary Productivity; Reco = ecosystem respiration; NEE = Net Ecosystem Exchange.

Table 1. Information on the vineyard management in the experimental site (data are shown per hectare and per year).

	Values	**Data source**
Vineyard lifetime (years)	14	Farmer interview
Vine plants (n)	5952	Farmer interview
Fuel consumption for field practices (l)	384.6 (14.27 GJ)	Farmer interview
Fuel consumption for travels (l)	36.3	Farmer interview
Nitrogen fertilization (kg)	22.5 (chemical); 5 (organic)	Farmer interview
Pruning (kg d.m.)	703.6	Direct sampling
Grapevine residue management	Cut and incorporated into the soil	Farmer interview
Grape yield (kg)	10000	Farmer interview
Grapefruit components (stalks, grape skin, and grape seeds) (kg)	3500	Average value from lab analysis
Grape juice (kg)	6500 (22 Brix degree)	Average value from lab analysis
Human work (hr)	92.8	Farmer interview

Table 2. GHG emissions during the grape production phase. Data are expressed per kg of grape yield.

	Direct CO_2 emissions	**kg kg^{-1}**
A	Fuel consumption for field practices	0.1056
B	Fuel consumption for travels	0.0100
C	Human work	0.0043
D	Crop residues	0.1289
E	Grape yield	0.4783
	Indirect CO_2 emissions (from N)	
F	Fertilization application	0.0130
G	Soil management	0.1320
H	Crop residues	0.0009
I	Grapefruit components	0.0070

Table 3. Monthly values of Net Ecosystem Exchange (NEE), Gross Primary Productivity (GPP), and ecosystem Respiration (Reco) calculated during the measurement period (October 2009-September 2010).

		NEE	**GPP**	**Reco**
		(g C m^{-2} $month^{-1}$)		
Year	**Month**			
2009	October	27.69	-66.58	94.27
	November	40.50	-16.21	56.71
	December	34.15	-15.32	49.48
2010	January	20.19	-31.06	51.24
	February	-3.43	-59.19	55.75
	March	32.67	-46.73	79.40
	April	46.16	-39.89	86.05
	May	-35.22	-126.01	90.80
	June	-92.93	-227.16	134.25
	July	-100.04	-229.34	129.31
	August	-108.12	-198.16	90.04
	September	-56.59	-132.85	76.26