A comprehensive greenhouse gas (GHG) budget assessment at farm level showing the potential carbon neutrality of sustainable viticulture.

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Abstract

Sustainable agricultural practices are often proposed as attractive strategies enabling food production systems to maintain a balance between productivity and environmental preservation to respond to the impacts of climate change. However, information on the actual contribution to climate change provided by sustainable managed agrosystem is lacking in literature. This study aims at quantify the actual impact on the climate system of sustainable practices applied to a grape-to-wine system in Italy. The overall budget of greenhouse gas (GHG) fluxes is assessed at wine farm level, through an integration of methods, including the eddy covariance technique, the life cycle assessment and the IPCC guideline. All the components of the GHG budget have been considered: the (a) biogenic and (b) anthropogenic GHG emissions related to the grape production and the (c) carbon sink function of the vineyard. Moreover, for a complete and comprehensive assessment of the full grape-to-wine system, the study evaluates also the (d) anthropogenic GHG emissions generated by the grape transformation process into wine.

At the vineyard level, the overall GHG budget resulted to be close to zero, showing a potential carbon neutrality of sustainable viticulture. In particular, the sum of biogenic GHG emissions (a) and carbon sink function (c) of the vineyard resulted in a net carbon sink with a potential contribution to climate change mitigation of 0.27±1.11 Mg CO_2eq year^{-1} per unit of land (hectare); while the anthropogenic GHG emissions (b) from the field operations for the sustainable management of the vineyard accounted for 0.24±0.05 Mg CO_2eq ha^{-1} year^{-1}. The sustainable transformation process (including vinification, bottling and packaging) still remains a source of GHG emissions (d), albeit sensibly reduced respect to average values in literature.

Therefore, the findings of the study indicates that (i) the sustainable wine making process has in general a lower contribution to climate change in terms of anthropogenic GHG emissions per hectare or per bottle of wine, and that (ii) sustainable practices applied to viticulture can turn the system into a net carbon sink able to totally compensate anthropogenic GHG emissions generated for the sustainable management in the field. Hence, sustainable viticulture is a low-carbon agriculture allowing food production with a potential carbon neutrality, thus without contributing to exacerbate climate change.

Max 6 Keywords: climate change mitigation, adaptation, wine, vineyard, LCA, Eddy covariance.

1. Introduction

Viticulture is a relevant and widespread agricultural system of the rural landscape with more than 7 million of hectares in the world, half of which are concentrated in Europe (FAOSTAT, 2018), where Italy, France and Spain represent the main wine producers with an average annual production of about 130 million hectoliters of wine (OIV, 2018a). Moreover, the cultivation of vineyards is expanding also outside the traditional wine-growing areas of Europe with the "new world wine producers" Argentina, Chile, California and United States, New Zealand, Australia, South Africa and China (FAOSTAT, 2018), as suitability for viticulture is changing under climate change (IPCC, 2014a; IPCC 2014b; Bonfante et al., 2018) with potential new area becoming appropriate for viticulture. Furthermore, grape production and wine consumption are expected to increase following the projected growth of human population from 7.2 to 9.8 billion by 2050 (UN, 2017). However, it is worth noting that climate change is directly influencing the agricultural sector and will continue to affect also grape production with even more frequent and intensive extreme events, such as droughts, floods and storms, leading to changes also in local weather patterns that will affect ecosystems with possible increase of plant diseases and competition for natural resources (IPCC, 2014a; IPCC 2014b; FAO, 2017), compromising food security (FAO et al., 2017).

At the same time agriculture is one of the main contributors in terms of greenhouse gas (GHG) emissions causing global climate change, being responsible of approximatively one fifth of global emissions (IPCC, 2014c). In particular, intensive agriculture, with high levels of inputs, significantly impacts on the environment causing land degradation, deforestation, declines in biodiversity, depletion of soil, air and water pollution and high levels of greenhouse gas emissions (Mengel, 1993; McLaughlin and Mineau, 1995; IPCC, 2014a; IPCC, 2014b; Dudley and Alexander, 2017; Muhammed et al., 2018). Nevertheless, the rural landscape represents a multifunctional system (Winkler et al., 2017) able to provide a plethora of important economic, cultural and ecological services to the local communities and to the global system, including carbon sequestration. Vineyards in Mediterranean and temperate areas are potential good examples in particular for the latter service, as perennial agricultural crops can store carbon both in the permanent woody structures and in the soil (Kroodsma and Field, 2006; Williams et al. 2011; Scandellari et al., 2017), with a potential contribution to climate change mitigation. However, the intensive management of vineyards and of the grape-to-wine transformation system influence the GHG emissions of grape and wine production and can cancel out and even reverse the positive effects of carbon sequestration, with a potential opposite effect causing climate change.

Climate change has been identified as one of the key factors undermining food security and causing world hunger that is on the rise with an increase of undernourished people from 777 million in 2015 to 815 million in 2016 (FAO et al., 2017). In this regard, the main international agreements on climate as the Kyoto Protocol and the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC), as well as the main Decisions and Regulations at European and national level, ask for concrete action for climate change mitigation and adaptation, also in the agricultural sector. Therefore, farming systems need to adjust requiring actions to both mitigate and adapt to climate change and to natural resource scarcities. In particular, the priority need for the world population should be to identify and foster agricultural practices that aim at increasing food security and can at the same time have climate change mitigation benefits.

Sustainable agriculture seems to represent a possible solution to support food security and respond to the 2030 Agenda for Sustainable Development which encompasses the Paris Agreement under the UNFCCC and the Sustainable Development Goals (SDGs). According to FAO (2017), a climate smart agriculture (CSA) should simultaneously tackle the challenges to sustainably increase productivity and incomes, build resilience to the impact of climate change and contribute to climate change mitigation. Moreover, organic farming has been recognized as a key strategy to address together climate change adaptation and mitigation, enabling also to maintain and improve the financial performance of agriculture sector (Sacchelli et al., 2017) as well as the productivity and quality of food. Organic farming can also have benefits in terms of protection of the biodiversity, due to a more robust balance between resource availability, living organisms and productivity, at the same time maintaining pest and disease at the lowest level (Provost and Pedneault, 2016). Furthermore, practices such as tillage and soil preparation have been historically applied in conventional agriculture (Triplett and Dick, 2008) or in other ecosystems such as forests (Hörnfeldt et al., 2012) to enhance new planting and soil productivity or for weed control. However, recent studies reviewed by Busari et al. (2015) demonstrated that no-tillage and the maintenance of grass cover in permanent crops can represent effective sustainable practices able to not negatively affect or even enhance productivity while leading to several environmental and climate benefits. Also the crop residues management can represents a resource in terms of organic fertilization improving soil productivity and crop production and maintaining high levels of soil organic matter (Reicosky and Wilts, 2005; DeVetter et al., 2015; Cirigliano et al., 2017; Devi et al., 2017).

Accordingly, sustainable agricultural practices (including organic farming, reduced use of chemicals, reuse of crop waste for organic fertilization, no-till and grass cover in perennial crops for soil protection) can best respond to the impacts of climate change enabling food production systems to maintain a balance between productivity and environmental preservation. In this regard, there is a growing interest in the scientific community in understanding the nexus between agricultural production, environmental impact and climate change (Aydinalp and Cresser, 2008). Moreover, food consumers' awareness and education are increasing with a consequent growing willingness in consumption of healthy and organic food with less environmental impact (Barber, 2009, Agovino et al 2017, Ricci et al., 2018), thereby sustainable agriculture has experienced a steady increase in European countries (Laureti and Benedetti, 2018) encouraged also by local to global policies (e.g. the European Common Agricultural Policy – EU CAP).

Flores (2018) underlines that many studies in literature provide useful assessments of the impacts of agriculture and food products on the environment and on climate but only a few identifies sustainable practices for food production and evaluates their impact on climate and environment. Furthermore, most of the existing studies consider the impacts of different phases of the food production process through the product's life cycle, but they often ignore ecosystem services provided by the agricultural systems, including carbon sequestration (Pizzigallo et al., 2008; Chiriacò et al., 2017). An integration of methods that may be potentially complementary is therefore favorable (Pizzigallo et al., 2008, Bosco et al., 2013) for a full and complete assessment of the impact on climate of sustainable agricultural practices.

In order to contribute to a better understanding of the actual impact of sustainable agriculture on the climate system, this study aims at quantifying the overall budget of the GHG fluxes of a sustainable grape-to-wine system. In particular, the study aims at assessing all the GHG emissions and removals occurring at wine farm level through an integration of methods that aim at quantifying the impact on climate of sustainable wine production in terms of GHG emissions and mitigation potential provided by carbon sequestration. The comprehensive GHG budget is therefore assessed in this study considering all the involved components, such as both the (a) biogenic and (b) anthropogenic GHG emissions generated for the grape production and the (c) carbon sink function of the vineyard. Moreover, for a complete assessment of the full grape-to-wine system, the study evaluates also the (d) anthropogenic GHG emissions generated by the grape transformation process into wine.

Hence, this study represents a first optimal example for a comprehensive understanding of the overall GHG budget and of the consequent actual contribution to climate change of sustainable viticulture. Such kind of information provided by this study is of wide interest in the scientific community working with agrosystem and climate change and acquires great importance also for decision makers in the evaluation of the effect of agro-environmental measures of the Common Agricultural Policy (CAP) and in the framework of the reporting and accounting obligations under the UNFCCC and its Kyoto Protocol and the UE decision 529/2013.

2. Experimental site description

The GHG budget is assessed in this study in a sustainable farm that produces organic and high-quality wines. The wine farm is located in Italy in Castiglione in Teverina (Viterbo) in the northern part of the Lazio region (Central Italy). The study area is in the Vulsino volcanic apparatus of central Italy, where the geological formation consists in volcanoclastic deposits, predominantly ignimbrites composed by tuffs, lapilli and inconsistent ash. The soils are classified as Entisols, Xeropsamments group in Soil Taxonomy (USDA, 2010). They are slightly acidic and well drained as a consequence of the xeric moisture regime, texture and slight inclination of the ground (generally less than 5%). The climatic conditions are characterized by average annual precipitations of about 788 mm and average daily temperatures around 23.9 °C during the hottest month of July and around 5.5 °C during the coldest month of January (average data for the period 1982-2012, source: Climate-data.org).

The whole process of wine production is directly carried out in the farm, from the grape cultivation to the transformation into wine, till the packaging of the final bottles of wine (Figure 1). The GHG budget is assessed at farm level considering the GHG emissions and removals occurred during the temporal framework of 12 months, corresponding to a productive year, from August 2014 to July 2015, including the grape harvesting of 2014 and the following field operations until the successive grape harvesting.

The vines of the grape variety Montepulciano (Violone) were 10 years old in 2014 and the vineyard is trained to a lateral cordon, spur pruned, with a plant density of 5.000 vines per hectare and planting distance of 2.5 between rows and 0,8 m between vines in the same row (Table 1).

Sustainable management practices are applied in the farm for the wine making process both in the field and in the cellar. The most relevant sustainable practices applied in the field include:

- reduced use of chemicals (limited amount of copper and sulphur allowed according to organic farming criteria - Reg. (EC) n. 834/2007 and Reg. (EC) n. 889/2008);
- no-till and grass cover for soil protection;
- removal from the field of the shredded pruning material so to avoid the spread of pests and diseases and reduce pest treatments;
- reuse of vineyard residues (pruning and grapefruit residues) for compost production;
- application of on-farm produced compost for soil organic fertilizer.

Sustainable management practices applied in the cellar aim at reducing the use of energy for electricity and applying sustainable packaging solutions with particular regard to glass bottles, that usually represent the major sources of GHG emissions in wine production (Iannone et al., 2016; Martins et al., 2018):

- energy saving thanks to the natural cooling of the cellar dug into the rock;
- ultralight glass bottles (360 g) with 10% less of weight respect to standard bottles.

The grape harvest took place on the 5th October 2014 (Table 2) with a grape yield of 2.5 tons ha^{-1}. The grape yield was particularly low respect to the average values of 8-10 tons per hectare registered in Italy in the period 2000-2016 (OIV, 2018a; FAOSTAT, 2018) and considering the maximum yield of 13 tons per hectare allowed by the specifications for the production under the appellation of origin of the grape variety Violone (DOC "Colli Etruschi Viterbesi" o "Tuscia" - D.M. 30.11.2011 - G.U. 295 20.12.2011). The low yield is due to two main reasons. On one side, organic viticulture and high-quality wine production have a still general lower productivity, due to the limited use of chemical inputs and to the reduced buds number as a result of pruning and training practices that lead to lower quantity of grape but with higher quality parameters (Döring et al., 2015; Dobrei et al., 2016). On the other side, unusual weather events occurred in central Italy in late spring 2014, with 100 mm of rain in May and 124 mm in June recorded by the farm weather station, respect to the average of 54 mm in May and 54 mm in June (average data for the period 1982-2012, source: climate-data.org). This led to extremely unfavorable conditions for viticulture: higher frequency and consistency of precipitations and the consequent wetter conditions favored pathogens outbreaks, while the few sun hours due to cloudiness slowed the vegetative vine development (Fregoni, 2013). However, this low level of yield registered in 2014, beside reflecting the likely ongoing effects of climate change that are projected also to worsen in the future (IPCC 2014a; IPCC 2014b; IPCC 2014c), doesn't influence the analysis of the GHG budget that is conducted per unit of area (hectare). Rather, the assessment of the GHG budget considering lower yields, respect to average conditions, represents a conservative approach in which the impact in terms of anthropogenic GHG emissions (see section 4.3) is partitioned by a smaller amount of product (i.e. less number of bottles produced) providing possibly higher emissions per unit of product, thus avoiding the risk of underestimation of emissions (IPCC, 2006).

The grape was manually harvested with the help of a tractor and a trailer for the transport of grapes to the cellar. The first field operation after the grape harvest took place in October 2014 and consisted of a mowing for weeds control between the vines under the row with the use of the tractor. The manual pruning and binding of the grape vines occurred in February 2015. In mid-April

2015 a mowing for weeds control between the rows was carried out with the use of the tractor. Another mowing with tractor for weeds control between the vines under the row occurred in the first half of May 2015, followed by a mowing for weeds control between the vine rows on June 2015. Weed residues from mowing are shredded and leaved on the soil, while the vines pruning material is shredded and collected to be composted in the farm, together with the grapefruit residues (stalks, grape skin and grape seeds) resulting from the vinification, and re-used on farm as organic fertilization of the soil. The compost produced from the vineyard residues are then distributed on-farm under the row with the aim of fertilizing the soil, limiting the spread of weeds and reducing soil erosion (DeVetter et al., 2015; Cirigliano et al., 2017). No irrigation occurs and no chemicals for fertilization or weeds control are applied, with the exception of limited amounts of copper oxide and sulphur for pest control, according to the organic farming criteria (Reg. (EC) n. 834/2007 and Reg. (EC) n. 889/2008). Four treatments with a total amount of 1,75 kg ha^{-1} of copper oxide and 1,60 kg ha^{-1} of Sulphur were carried out between May and July 2015 (Table 2).

The transformation process of the grape into wine is carried out directly in the cellar and it starts immediately after the grape harvest. It includes the vinification, the bottling and the packaging of the wine, with a total production of 1.500 L of wine per hectare, corresponding to 2.000 bottles of wine of 0,75 L per hectare (Table 1). The organic wine production process implies the minimum use of chemical inputs as possible. Moreover, the cellar, that is north-west exposed and dug into the rock, takes advantages from the natural cooling with consequent reduced energy consumption for electricity and lower GHG emissions for the temperature control during the wine making process. Furthermore, the use of ultralight glass bottles for the packaging implies a further reduction of anthropogenic GHG emissions, being the glass bottles one of the main contributors of GHG emissions in the wine making process (Iannone et al., 2016; Martins et al., 2018).

The grapefruit residues of the vinification process (stalks, grape skin and grape seeds) are collected to be composted in the farm together with the pruning material and re-used as organic fertilization of the soil. At the end of the wine production process for the period 2014-2015 about 4 tons ha^{-1} (fresh weight) of final compost were produced by the vineyard residues, of which about 3,1 tons ha^{-1} (fresh weight) resulting from the annual pruning material and 0,9 tons ha^{-1} (fresh weight) of grapefruit residues resulting from the vinification.

Table 1. Characteristics of the vineyard system (Data source: farm registry).

	Values
Vineyard age (years)	10
Vine plants (n ha^{-1})	5.000
Grape yields (ton/ha^{-1})	2,5
Wine production (L ha^{-1})	1.500
Bottles of wine of 0,75 L (n ha^{-1})	2.000

Table 2. Annual operations for the agronomic management of the vineyard for the period 2014-2015 (Data source: farm registry).

Field operations	**Period**
Grape harvesting	5th October 2014
Mowing for weeds control under the row	October 2014
Manual pruning and binding of the grape vines	February 2015
Pruning shredding and collection	March 2015
Mowing for weeds control between the rows	mid-April 2015
Mowing for weeds control under the row	May 2015
Mowing for weeds control between the rows	June 2015
Four treatments for pests control	May-July 2015

3. Methodology to assess the comprehensive GHG budget

The GHG fluxes of agroecosystems can represent either an emission of to the atmosphere or an uptake from the atmosphere; therefore, the GHG contributions to the total budget can have positive or negative sign. For the purpose of this study, a positive (+) sign indicates an emission to the atmosphere, while a negative (-) sign represents an uptake from the atmosphere. The GHG budget is calculated as the algebraic sum of GHG emissions and removals occurring during a productive year, from August 2014 to July 2015 (12 months), including the grape harvesting of 2014 and the following field operations. The GHG budget is assessed at farm level including the field phase for the cultivation and management of the vineyard as well as the transformation process of grape into wine (Figure 1).

The total GHG budget from the vineyard system up to the wine production (GHG_W) is calculated (Eq. 1) as the sum of the (a) biogenic (F_{BIOG}) and (b + d) anthropogenic (E_{ANTR}) GHG emissions and/or removals, including CO_2, CH_4 and N_2O, and the (c) carbon stock changes in the vineyard due to the agronomic operations for the field management (F_{MG}).

The GHG fluxes are assessed differently depending on the gas and its origin: biogenic vineyard–atmosphere fluxes of CO_2 (i.e. net ecosystem exchange - NEE) are measured using eddy covariance (EC) technique; other biogenic emissions of CO_2, N_2O and CH_4 are calculated applying the methodologies developed by the Intergovernmental Panel on Climate Change (IPCC); anthropogenic emissions of the three GHGs due to the productive process are estimated via a life cycle assessment (LCA) from the vineyard to the bottle of wine; while the annual carbon stock changes due to the agronomic management were assessed by direct measurements.

$$GHG_W = F_{BIOG} + F_{MG} + E_{ANTR} \quad (1)$$

where:

$$F_{BIOG} = F_{CO2(EC)} + F_{CO2(C)} + F_{CH4(C)} + F_{N2O(C)} + F_{N2O(S)} \quad (2)$$

and

$$F_{MG} = F_S + F_G + F_{PB} \quad (3)$$

and

$$E_{ANTR} = E_{Field} + E_{Cellar} \quad (4)$$

In Eq. (2), $F_{CO2(EC)}$ represents the biogenic CO_2 vineyard–atmosphere fluxes measured with the EC technique, while $F_{CO2(C)}$, $F_{CH4(C)}$, $F_{N2O(C)}$ and $F_{N2O(S)}$ represent the biogenic emissions of carbon dioxide, methane and nitrous oxide from on-farm compost production and soil management calculated according with IPCC (2006).

In Eq. (3), F_S represents the organic carbon added to the soil organic carbon (SOC) stock through the annual soil organic fertilization with compost produced on farm by agricultural wastes. F_G is the carbon removed with the harvested grape, while F_{PB} is the carbon removed with the pruning of biomass.

In Eq. (4), E_{Field} represents the anthropogenic GHG emissions coming from the field operations for the management of the vineyard, while E_{Cellar} represents the anthropogenic GHG emissions coming from the transformation process of grape into wine (including vinification, bottling and packaging), both assessed with a LCA approach.

The total GHG budget of the vineyard system up to the wine production is expressed in CO_2 equivalent (CO_2eq) according to the global warming potential (GWP) emission factors with a time horizon of 100 years (Myhre et al., 2013) which assigned 1 GWP to 1 kg of CO_2, 28 GWP to 1 kg of CH_4 and 265 GWP to 1 kg of N_2O.

3.1 Biogenic fluxes of GHGs

The biogenic GHG fluxes related to the vineyard system include the vineyard–atmosphere exchanges of biogenic CO_2 fluxes. Moreover, for a comprehensive GHG assessment of the farm system, the biogenic emissions of carbon dioxide, methane and nitrous oxide due to the compost production process and the soil management following the compost distribution are included in the calculation (F_{BIOG} - Eq. 2).

The three GHGs included in the budget (CO_2, CH_4, N_2O) have been calculated with different techniques depending on their origin. Fluxes of CO_2 ($F_{CO2(EC)}$ in Eq. 2) to and from the whole ecosystem (soil + vegetation, i.e. the net ecosystem exchange - NEE) have been measured in the field using the eddy covariance (EC) methodology. Other CO_2, CH_4 and N_2O biogenic emissions from compost production ($F_{CO2(C)}$, $F_{CH4(C)}$, $F_{N2O(C)}$ in Eq. 2) and soil management ($F_{N2O(S)}$ in Eq. 2) instead have been extrapolated based on IPCC methodologies (IPCC, 2006), as no direct measurements were available.

3.1.1 Eddy covariance measurement for biogenic CO_2 fluxes

The EC technique allows the calculation of on-site fluxes of gases to and from the whole ecosystem (soil + vegetation, i.e. the net ecosystem exchange - NEE) via the covariance between its entity and vertical wind velocity. High frequency measurement of these and other complementary variables are performed using an ultrasonic anemometer and a fast-response gas analyzer (see Aubinet et al., 2012 for further details on the technique). The EC setup in the investigated vineyard consisted of a sonic anemometer Gill WindMaster (Gill, Lymington, UK) and an open-path infrared gas analyser (LI-7500, LICOR, Lincoln, NB, US). The additional instrumentation included a weather station for measuring air temperature, air pressure, air humidity and other relevant meteorological variables. Data were collected at a frequency of 10 Hz, and then processed using EddyPro software from LICOR. The fluxes were calculated on a 30 minutes period, and the most important corrections were carried out including coordinate rotations of the sonic anemometer data, time-lag compensation, low and high frequency spectral corrections (see Aubinet et al., 2012).

Moreover, the half-hourly time series of CO_2 flux were further corrected for storage component, quality checked, de-spiked and filtered based on calm conditions (u^*), applying a combination of two approaches: (i) as described in Papale et al., (2006) and in Reichstein et al., (2005); (ii) as reported in Barr et al., (2013). The NEE values falling in the median (50th percentile) were considered, with a range of uncertainty of NEE values filtered by 5th and 95th percentile of the distribution of u^* thresholds values. The filling of data gaps resulting from the filtering of the time series was performed according to Reichstein et al (2005). The final time series was then aggregated to daily, monthly and annual time scales.

3.1.2 Other biogenic CO_2, CH_4 and N_2O emissions

Biogenic emissions from compost production

The composting of the vineyard residues is an aerobic process in which, according to IPCC (2006, vol. 5 ch. 4), a large fraction of the degradable organic carbon is usually converted in CO_2. However, a few amount of methane is formed in anaerobic sections of the compost, albeit it is oxidized to a large extent in the aerobic sections of the compost, and some N_2O emissions are produced as well (IPCC 2006, vol. 5 ch. 4). At the end of the wine production process for the period 2014-2015 about 4 tons ha^{-1} (fresh weight) of compost derived by on-farm organic residues were applied in the field as organic fertilization (see section 2). Thus, to asses CH_4 and N_2O emissions from the compost production process ($F_{CH4(C)}$ and $F_{N2O(C)}$ in Eq. 2), the Tier 1 approach of IPCC (2006, vol. 5 ch. 4) was applied for the purposes of this study using the default average emission factor of 4 g CH_4 and 0,24 g N_2O per kg of fresh compost, as proposed by IPCC (2006).

The CO_2 emissions resulting from the aerobic fermentation due to the compost production ($F_{CO2(C)}$ in Eq. 2) has been estimated considering the difference between the amount of carbon found in the mature compost (corresponding to the 43±2,1% of the dry matter with 70% humidity, as derived by laboratory analysis) respect to the initial carbon contained in pruning and grapefruit residues (see section 3.2.1), at the net of the carbon already counted in methane emissions from the compost production process.

Biogenic emissions from soil management

The direct and indirect N_2O emissions from the compost application to soil for fertilization ($F_{N2O(S)}$ in Eq. 2) were estimated with a Tier 1 approach according to IPCC (2006). The N content of the compost was calculated by laboratory analysis and corresponds to 2±0,2% of the total dry matter that was assessed to be the 30% of the fresh weight. Therefore, the compost incorporation implies a total N input to the soil of 25 kg N ha^{-1}. We calculated direct emissions of N_2O from decomposition and mineralization of compost using the default value (EF_1) of 0,01 for the equation 11.1 as reported by IPCC (2006). Indirect N_2O emissions from atmospheric deposition of N volatilized from the compost use were calculated applying the default value of 0,2 (IPCC, 2006) for the fraction of the applied N fertilizer contained in the compost that volatilizes as NH_3 and NO_x and the emission factor for N_2O emission from N atmospheric deposition (EF_4) of 0,01 as reported for the equation 11.9 by IPCC (2006). Indirect N_2O emissions from leaching were calculated using the default value of 0,3 (IPCC, 2006) to estimate the fraction of N contained in the compost applied to the vineyard managed soil that is lost through leaching and runoff and applying the default emission factor (EF_5) of 0,0075 as indicated for the equation 11.10 by IPCC (2006).

Methane fluxes from soil are usually related to high concentrations of water in the soil (IPCC, 2006; Tate, 2015), thus methane emissions from soil due to the compost application for soil fertilization were assumed to not occur, considering that the investigated vineyard is not irrigated.

3.2 Annual carbon stock changes due to the agronomic management

The agronomic management of the vineyard implies field operations that can influence the annual carbon stock changes of the vineyard system (F_{MG} - Eq. 3). In particular, the compost application under the rows implies an increase of the SOC content, while the pruning of biomass as well as the grape harvest implies a loss of carbon from the system.

3.2.1 Carbon loss from grape harvest and pruning of biomass

A certain amount of carbon accumulated by the vines during the summer is partitioned into fruit and annual vegetation and is annually removed from the vineyard system with the pruning of biomass and the grape harvest and then released as part of the wine fermentation process. This component is not tracked in the calculation of NEE (Longbottom and Petrie, 2015). Therefore, for a comprehensive GHG accounting of the vineyard system these carbon stock variations due to the agronomic management should be quantified and deducted from the GHG budget.

The carbon removed with the grape harvest in October 2014 (F_G in Eq. 3) was calculated in two different ways for the grape juice and the other grapefruit components (stalks, grape skin and grape seeds). Considering the annual wine production of 1.500 liters ha^{-1}, the carbon content of the grape juice was calculated by means of the Brix degrees in the wine must (derived by laboratory analysis) and the molecular weight of the sugar components (Ribereau-Gayon et al., 2006; OIV, 2018b). Whereas, an average moisture content of 80% on fresh weight (as derived by laboratory analysis) and a carbon content of 47% on the dry matter (IPCC, 2006 vol. 4 ch. 4) were considered to assess the carbon loss from the 0,9±0,2 tons ha^{-1} of grapefruit residues directly measured as resulting from the vinification process (see section 2).

The carbon removed with the pruned biomass in February 2015 (F_{PB} in Eq. 3) was directly measured in the field by weighing representative samples of pruning residues form different vines. The pruned biomass was equal to 3,1±0,76 tons ha^{-1} (fresh weight). A sub-sample was then exsiccated at 65°C in a forced-air oven to constant weight according to Keller and Koblet (1995) to assess the dry matter (54% humidity) and calculate the carbon loss, considering the carbon content 47% of dry matter (IPCC, 2006).

3.2.2 Increase of SOC from compost application

The application of compost to the vineyard, besides representing a substitute for synthetic fertilizers, may entail a significant increase in soil carbon sequestration (Favoino and Hogg, 2008; Mondini et al., 2007). In fact, the application of on-farm produced compost implies a return to the vineyard system of a fraction of the organic carbon previously subtracted with the grape harvest and the pruning of biomass. Part of the organic carbon contained in the compost annually added to the vineyard is emitted in atmosphere as CO_2 through the soil respiration and is already measured with the EC technique (see paragraph 3.2.1), while another part remains in soil inducing an increase in the SOC stock of vineyard (F_S in Eq. 3), as observed also by Ren et al. (2017). The application of on-farm produced compost to the vineyard is annually performed since the planting of the vines (2004), with about 4 tons ha^{-1} (fresh weight) per year of compost for the period 2014-2015 (see section 2). However, the SOC stock variations related to management practices, including the compost application, occur with non-linear dynamics during the following 20 or more years (IPCC, 2006; Chiti et al., 2018). Therefore, a spot measure on a yearly basis of the SOC stock change could not be representative, whereas a long-term trend of SOC increase attributable to the compost application should be considered to extrapolate the average annual rate. For this reason, the main existing literature has been reviewed to derive an average annual rate of SOC increase from compost application (Triberti et al., 2008; Bos et al., 2017; Freibauer et al. 2004; Lou and Nair 2009).

3.3 Anthropogenic emissions of GHGs

The field operations for the agronomic management of the vineyard and the transformation process in the cellar of grape into wine imply the production of a certain amount of anthropogenic GHG emissions (E_{ANTR} - Eq. 4).

The overall anthropogenic GHG emissions associated with the production process across its overall life cycle, also known as the carbon footprint (CF), were assessed via a LCA applied with a "cradle to gate" approach (ISO, 2006b; Finkerbeiner et al., 2006): the production and transport of raw materials, the field operations, the transformation process in the cellar from grape to wine and the packaging of the final bottle of wine were included in the boundary system (Figure 1). The CF left by human activities was assessed considering both the functional unit (FU) per unit of land (1 hectare of vineyard, FU_{ha}) and per unit of product (1 bottle of wine of 0,75 L, FU_{Bottle}).

The data used to perform the LCA refers to the overall wine making process for the period 2014-2015 and were directly collected on site from invoices, registries, measures and archives of the farm (Table 3, Table 4 and Table 5). Only when primary data were not available, conservative data were derived from literature and international databases, which support environmental assessments (i.e. Ecoinvent database) or calculated using appropriate models (IPCC, 2006).

The LCA applied in this study follows an attributional approach where the environmental impacts in terms of GHG emissions are quantified and allocated in relation to the life cycle of the production process. The methodology we adopted follows the Product Category Rules (PCR) for Wine of Fresh Grapes (EPD, 2015a) and for Fruits and Nuts (EPD, 2015b) based on the ISO 14025 standard on Environmental Product Declaration (ISO, 2006a) and in accordance with the international standards ISO 9001 "Quality management systems"; ISO 14001 "Environmental management systems"; ISO 14040 "LCA - Principles and procedures"; ISO 14044 "LCA - Requirements and guidelines" (ISO, 2006b; Finkbeiner et al., 2006) and ISO 14067 "Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification and communication". The data were processed by the LCA software SimaPro 7.3.3.

3.3.1 Anthropogenic GHG emissions from the vineyard

All the field operations described in section 2 and summarized in Table 1 and Table 2 were considered to assess the CF at the vineyard level (E_{Field} in Eq. 4). The production, packaging and transport of raw materials, such as copper oxide and sulphur, iron yarns for binding and fuel for the agricultural operations, were also included in this phase, as well as the transport of the grape to the cellar (Table 3 and Table 5).

Furthermore, as the vineyard is on a land, which has been used for agricultural purposes for longer than 25 years, we didn't consider the GHG emissions from land use change, according to EPD (2015b) and IPCC (2006). For the same reason, also GHG emissions related to the operations for the initial establishment of the vineyard were not included as the life time is expected to be longer than 25 years (EPD, 2015b).

Table 3. Life cycle inventory for the field phase

Field phase	**Quantity per FU_{ha}**	**Quantity per FU_{Bottle}**	**Type of data**	**Data source**
Copper oxide	1,75 kg	0,88 g	Primary	Farm registry
Sulphur	1,60 kg	0,8 g	Primary	Farm registry
Iron yarns	1,78 kg	0,89 g	Primary	Invoices
Organic fertilization	4 tons	2 kg	Primary	Directly measured (fresh weight)
Fuel consumption	212 L	89 g	Primary; Secondary	Farm registry; Specific weight of diesel 0,84 kg/L (Nemecek and Kagi, 2007)
Packaging of copper oxide and sulphur (paper)	15 g	0,008 g	Primary	Directly measured

3.3.2 Anthropogenic GHG emissions from the transformation process in the cellar

The CF of the transformation process in the cellar (E_{Cellar} in Eq. 4) includes the vinification, the bottling and the packaging of the final wine. The total energy required in the cellar for the transformation process is 0,66 kW per liter of produced wine (Table 4) and is provided by the national energy network with the average Italian energy mix. According to (Dones et al., 2007) an emission factor of 650 g CO_2eq is assigned per kWh of consumed electricity derived by the Italian energy mix at medium voltage.

During the vinification process 40 g of yeast and nutrients for the yeast are used per 100 liter of wine for the fermentation and 20 g of sulphur dioxide are added per 100 liter of wine for the preservation of wine during time. The bottling is carried out directly in the cellar and the final packaging is an ultra-light glass bottle of 0,75 liters, with a frontal and back label in recycled paper, a cork and a plastic cap seal, usually commercialized in cardboard boxes with six bottle each (Table 4).

The production, packaging and transport of raw materials, such as the yeast and the nutrients for the yeast, the sulphur dioxide, the glass bottles, the recycled paper labels, the corks, the cap seals and the recycled cardboard boxes were also included in this phase (Table 4 and Table 5). No detergents are used in the cellar as the cleaning process is carried out with an innovative technology based on the use of ozone that comes back to the air as oxygen avoiding the production of waste water.

Table 4. Life cycle inventory for the transformation process

Transformation process	Quantity per FU_{ha}	Quantity per FU_{Bottle}	Type of data	Data source
Electricity (IT energy mix)	990 kWh	0,5 kWh	Primary	Invoices
Yeast and nutrients for the yeast	0,6 kg	0,30 g	Primary	Farm registry
Sulphur dioxide	0,3 kg	0,15 g	Primary	Farm registry
Packaging of yeast and nutrients (aluminum)	12 g	0,006 g	Primary	Directly measured
Packaging of sulphur dioxide (plastic)	15 g	0,008 g	Primary	Directly measured
Glass bottle	720 kg	360 g	Primary	Directly measured
Frontal and back labels (recycled paper)	5 kg	2,5 g	Primary	Directly measured
Cork	9 kg	4,5 g	Primary	Directly measured
Cap seal (pvc)	1,6 kg	0,8 g	Primary	Directly measured
Cardboard box – for 6 bottles (recycled paper)	92 kg	46 g	Primary	Directly measured
Packaging for transport of the primary packaging (plastic, paper)	600 – 20 g	0,3 – 0,01 g	Primary	Directly measured

Table 5. Life cycle inventory for the transport of raw materials, fuel and packaging

Type of transport	From	To	Type of vehicle	Distance (km)
Grape	field	cellar	tractor and trailer	0,6
Fuel	regional storage	field	lorry 3,5-20 t	45
Copper oxide, sulphur, iron yarns	regional storehouse	field	van<3,5 t	40
Yeast and nutrients for the yeast, sulphur dioxide	regional storehouse	cellar	van<3,5 t	65
Glass bottles	regional storehouse	cellar	lorry 3,5-20 t	60
Frontal and back labels	regional storehouse	cellar	van<3,5 t	40
Corks	regional storehouse	cellar	lorry 3,5-20 t	500
Cap seals	regional storehouse	cellar	lorry 3,5-20 t	200
Cardboard boxes	regional storehouse	cellar	lorry 3,5-20 t	55

4. Results and discussion

4.1 Biogenic fluxes of GHGs of the vineyard system

The annual NEE of the vineyard system measured using the EC technique ($F_{CO2(EC)}$) was -150 g C m^2 $year^{-1}$ corresponding to -5,5±0,5 Mg CO_2eq ha^{-1} $year^{-1}$, with a range between -4,97 and -6,04 Mg CO_2 ha^{-1} included in the 5th and 95th percentile of the distribution (Table 6), which means a net annual carbon uptake by the ecosystem from the atmosphere.

The seasonal trend of NEE (Table 6, Figure 2) shows a net carbon sink with a carbon accumulation starting already before the budbreak due to the increased activity of the grass cover, with a peak during the summer when the vine canopy is fully developed. The carbon accumulation was lower and turned into a slight emission after the grape harvest when the vines started their dormancy. These results confirm the carbon sink activity due to no-till and to the presence of grass cover in the vineyard, as observed also by Gianelle et al (2015), Longbottom and Petrie (2015) and Marras et al. (2015). Therefore, these findings highlight the positive effect of such sustainable practices able to contribute to climate change mitigation allowing the system to act as carbon sink. Compared to other vineyard systems, the annual net carbon accumulation found in this study is in the range of mean values found in literature from 3 to 8 Mg CO_2eq ha^{-1} $year^{-1}$ (Chiriacò and Valentini, 2015; Gianelle et al. 2015; Marras et al., 2015; Brunori et al., 2016; Meggio and Pitacco, 2016; Scandellari et al., 2016; Morandé et al., 2017). However, the annual net carbon accumulation found in this study could also be even higher if considering the unfavorable weather conditions that in 2014 reduced the vines' productivity (as discussed in section 2). In this regard, in fact, some studies report annual net carbon accumulation in vineyards that can reach even values around 30 Mg CO_2eq ha^{-1} $year^{-1}$ (Guo et al., 2014; Chiriacò and Valentini, 2015; Gianelle et al. 2015). Hence, the results of this study confirm that sustainable managed vineyard systems could act as carbon sink thanks to their aptitude to sequester carbon in their permanent woody structures and in soils, even if the magnitude could depend by annual climate conditions.

On the other side, the crop residue management for the production of compost and its application to the soil imply a certain amount of biogenic GHG emissions (IPCC, 2006). The emissions from crop residue fermentation for the production of compost would have probably been produced also in case the residues were landfilled, even with a higher rate according with Lou and Nair (2009). The CO_2 emissions due to the aerobic fermentation during the compost production ($F_{CO2(C)}$) were assessed to be 1,25±0,1 Mg CO_2 ha^{-1}. The CH_4 and N_2O emissions from the compost production process ($F_{CH4(C)}$ and $F_{N2O(C)}$) were 0,45±0,4 Mg CO_2eq ha^{-1} and 0,26±0,29 Mg CO_2eq ha^{-1}, respectively. Soil emissions of N_2O due to the compost application for soil fertilization ($F_{N2O(S)}$) were estimated to be 0,15±0,02 Mg CO_2eq ha^{-1} (Table 8).

Therefore, the overall budget of the biogenic GHG fluxes of the system resulted in a net annual sink of -3,39±0,71 Mg CO_{2eq} ha^{-1} (Table 8, Figure 3).

Table 6. Monthly biogenic vineyard–atmosphere net ecosystem exchange (NEE) measured with Eddy Covariance technique (g C m^2). Positive (+) sign indicates an emission while negative (-) sign indicates a sink.

Period		NEE (g C m^2)		
		50th percentile	5th percentile	95th percentile
2014	August	-19,91	-19,09	-22,09
	September	3,82	4,09	3,27
	October	8,73	9,00	7,64
	November	13,64	15,00	12,00
	December	-0,27	4,09	-0,55
2015	January	-1,36	-1,09	-1,91
	February	-11,73	-9,82	-12,00
	March	-21,00	-19,64	-21,55
	April	-24,82	-24,27	-25,09
	May	-23,45	-22,64	-25,09
	June	-30,55	-28,64	-34,09
	July	-43,09	-42,55	-45,27
Annual NEE (g C m^2)		**-150,00**	**-135,55**	**-164,73**
Annual NEE (Mg CO_2 ha^{-1})		**-5,50**	**-4,97**	**-6,04**

4.2 Annual carbon stock changes due to the agronomic management

The annual carbon stock change due to the agronomic operations applied for the management of the vineyard, that includes the pruning of biomass, the grape harvesting and the compost application, resulted in a net GHG emission of 3,12±0,85 Mg CO_2eq ha^{-1} (Table 8, Figure 3).

In particular, in 2014 the total amount of pruned biomass in the vineyard was 3,1±0,76 tons per hectare (fresh weight), with a net carbon loss from the vineyard system corresponding to a GHG emission of 2,88±0,71 Mg CO_2eq ha^{-1} (F_{PB}). Moreover, the GHG emissions corresponding to the carbon removed by the system with the harvest of the grape (F_G) resulted to be 1,23±0,25 Mg CO_2eq ha^{-1}. Those emissions are calculated from the carbon contained both in the grape juice (1.500 liters ha^{-1}), corresponding to 0,92 Mg CO_2eq ha^{-1} and including emissions released as part of the wine fermentation process, and in the 0,9 tons ha^{-1} of grapefruit residues resulting from the vinification process, corresponding to 0,31 Mg CO_2eq ha^{-1} (Table 8).

On the other side, the application under the rows of the on-farm compost produced from crop residues as soil fertilizer implies a return to the vineyard of a fraction of the organic carbon previously subtracted with the grape harvest and the pruning of biomass. In fact, part of the organic carbon content of the compost applied to the soil is lost through the respiration process and already included in the EC measures, while another part is assumed to be transferred to the SOC pool, with a long-term carbon stabilization leading to an annual increase of the SOC content (Favoino and Hogg, 2008; Sánchez-Monedero et al., 2015). Many studies in literature demonstrate that sustainable agricultural practices such as organic farming or the application of organic fertilizer can potentially sequestrate more carbon in the soils and thus convert the soils to a net carbon sink

(Gattinger et al. 2012; Gregorich et al., 2007; Lynch et al., 2011). However, the annual SOC increase due to the compost application should be assessed as mean annual value of at least a twenty-year trend (IPCC, 2006; Chiti et al., 2018). Therefore, in absence of a such time series data, average values from existing literature were considered. Bos et al. (2017) modelled a mean SOC increase of 0,32 t C ha^{-1} $year^{-1}$ across a 25-year period of compost application, while Triberti et al. (2008) founded 0,16 t C ha^{-1} $year^{-1}$. Freibauer et al. (2004) suggest a potential SOC sequestration rate of 0,4 t C ha^{-1} $year^{-1}$ and a carbon sequestration of approximately 50 kg per ton of wet compost is reported by Lou and Nair (2009). From these values found in literature, the average annual rate of SOC increase due to the annual compost application was assumed to be 0,27±0,1 Mg C ha^{-1} corresponding to a net annual CO_2 removal of 0,99±0,4 Mg CO_2eq ha^{-1}. Thereby, the sustainable practice of on-farm compost application, besides representing an alternative to the use of synthetic fertilizers, thus avoiding the GHG emissions and other environmental impacts due to their production and use, contribute to climate change mitigation with a significant increase in soil carbon sequestration.

4.3 Anthropogenic GHG emissions from field management and transformation process

The anthropogenic GHG emissions resulting from the LCA analysis were 1,57±0,27 Mg CO_2eq ha^{-1} (Table 7) considering both the agricultural phase for the sustainable cultivation and management of the vineyard (responsible of an emission of 0,24±0,05 Mg CO_2eq ha^{-1}) and the transformation process of the grape into wine, including vinification, bottling and packaging (responsible of an emission of 1,33 Mg CO_2eq ha^{-1}).

As observed by Chiriacò et al. (2017), the CF assessed per unit of land (FU_{ha}), besides that per unit of product, allow a more comprehensive assessment of the real contribution to climate change especially for food products and agricultural areas where agronomic practices can influence the organic carbon content in soils and/or in woody perennial biomass. However, several studies in literature still assess the carbon footprint solely per unit of product. Thus, in order to allow any kind of comparison of results with other studies in literature, both FUs per unit of land (FU_{ha}) and per unit of product (FU_{Bottle}) have been assessed. Therefore, considering the number of bottles of wine produced per unit of area, that is of 2.000 bottles of 0,75 L per hectare, the carbon footprint for a bottle of wine is 0,79±0,14 kg CO_2eq $bottle^{-1}$ (Table 7).

The CF found in this study is consistent with the results obtained from other studies in literature that range on average between 0,6 and 1,6 kg CO_2eq $bottle^{-1}$ (Ardente et al., 2006; Gazulla et al., 2010; Bosco et al., 2011; Benedetto, 2013; Vázquez-Rowe et al., 2013; Fusi et al., 2014) with some studies that report also higher values up to 3,2 kg CO_2eq $bottle^{-1}$ (Vázquez-Rowe et al. 2012; Neto, et al. 2013). Diverse results in literature depend by different use of inputs and agronomic management under specific pedo-climatic conditions or by particular features of the transformation process or packaging characteristics. Also the boundaries of the analyzed system and the phases included in the analysis may provide differences in the estimate of the emissions. In fact, while almost all the studies in literature analyze the CF including the agricultural phase, the transformation process (vinification, bottling and packaging), some include also the vine planting phase and some others the distribution phase. The findings of this study, that encompasses the agricultural phase and the transformation process (including vinification, bottling and packaging), show a low value of total CF respect to average values in literature, thus demonstrating the sustainability of the analyzed wine making process with a low contribution to climate change in terms of anthropogenic GHG emissions. Moreover, the CF found in this study could also be even lower if considering the unfavorable weather conditions that in 2014 reduced the vines' productivity (as discussed in section 2).

Table 7 reports the CF per unit of area (FU_{ha}) and per unit of product (FU_{Bottle}) and shows the contribution of each phase in terms of anthropogenic GHG emissions assessed with the LCA approach. The agricultural phase for the sustainable cultivation and management of the vineyard is responsible for the 15% of the anthropogenic emissions, corresponding to 0,24±0,05 Mg CO_2eq ha^{-1} when considering the unit of cultivated land (FU_{ha}) and to 0,12±0,03 kg CO_2eq $bottle^{-1}$ when considering the unit of product (FU_{Bottle}). The transformation phase of grape into wine, including the vinification, the bottling and the final packaging, is responsible for the remaining 85% of the anthropogenic emissions, with 1,33±0,27 Mg CO_2eq ha^{-1} or 0,67±0,14 kg CO_2eq $bottle^{-1}$, of which the contribution attributable to the final packaging of the bottle of wine is 0,61±0,12 Mg CO_2eq ha^{-1} or 0,31±0,06 kg CO_2eq $bottle^{-1}$, corresponding to 46% of the total anthropogenic GHG emissions.

The main existing literature on CF of the wine making process shows that the agricultural phase contributes from 16% up to 40% (Bosco et al., 2011; Point et al., 2012; Vázquez-Rowe et al., 2012a; Benedetto, 2013; Neto et al., 2013; Rugani et al., 2013; Fusi et al, 2014) to the anthropogenic GHG emissions, with some studies showing that viticulture is one of the highest impacting phases of the wine life cycle (Vázquez-Rowe et al. 2012; Neto, et al. 2013; Ferrara and De Feo 2018).

The results of the LCA applied in this study show a lower contribution of the agricultural phase (15%) in sustainable viticulture to the total CF, with the main contribution within this phase represented by the fossil fuel consumption for the machinery used in the field (Table 7). The sustainability of the agricultural phase in this study is confirmed also as absolute value, both per unit of land with 0,24±0,05 Mg CO_2eq ha^{-1} and per unit of product with only 0,12±0,03 kg CO_2eq $bottle^{-1}$ against values found for viticulture in literature ranging from 0,33 to 0,80 and even to 2,5 kg CO_2eq $bottle^{-1}$ (Gazulla et al. 2010; Bosco et al. 2011; Point et al. 2012; Vázquez-Rowe et al. 2012; Neto, et al., 2013). The minor anthropogenic GHG emissions of the agricultural phase, respect to average values in literature, are due to the low level of inputs in sustainable viticulture that excludes the use of chemicals for fertilization and uses a limited amount of plant protection products (copper and sulphur in the limit allowed by the regulation for organic farming). In fact, the compost application to the vineyard substitutes the use of synthetic fertilizers, thus avoiding the GHG emissions and other environmental impacts due to their production and use. These findings are confirmed also by other studies that observed that the main sources of emissions within the agricultural phase in viticulture are mainly due to the fossil fuel consumption for the agricultural operations and to the use of fertilizers and pesticides that generate high polluting emissions both during their production and their subsequent application in the field (Notarnicola et al., 2003; Aranda et al., 2005; Ardente et al., 2006; Niccolucci et al., 2008; Pizzigallo et al., 2008; Point, 2008; Gazulla et al 2010; Bosco et al., 2011; Point et al., 2012; Benedetto 2013; Neto et al., 2013; Rugani et al., 2013; Fusi et al., 2014; Marras et al., 2015; Litskas et al 2017; Ferrara and De Feo, 2018). Therefore, the results of the study demonstrate that sustainable viticulture is a low-carbon agriculture with a lower contribution to climate change in terms of anthropogenic GHG emissions per hectare (or per bottle), as demonstrated also for precision viticulture by Balafoutis et al., (2017).

In the transformation process the main contribution of anthropogenic GHG emissions is provided by the energy consumption for the electricity used for machineries and the temperature control in the cellar, that accounts for 49% of the transformation emissions with 0,32 kg CO_2eq bottle^{-1} (Table 7), followed by the glass bottles that accounts for 36% of the transformation emissions with 0,24 kg CO_2eq bottle^{-1} (Table 7). The share of these two main contributors within the transformation phase is confirmed also by Iannone et al. (2016) and Martins et al. (2018) although the absolute values of the CF of these two phases in the analyzed sustainable wine making process are lower. The minor anthropogenic GHG emissions of the transformation process and packaging phase, respect to average values in literature, are due to the reduced use of energy for electricity in the cellar taking advantages from the natural cooling of the cellar that is dug into the rock and to the use of ultralight glass bottle (suggested also by Martins et al. (2018) as a strategy to reduce GHG emissions) that weigh 10% less than conventional wine bottles leading to lower emissions for their production and transport.

Thus, these findings demonstrate that sustainable viticulture and wine making process including sustainable practices both in viticulture and in the transformation process can have a low contribution in terms of GHG emissions, both per unit of land (FU_{ha}) and per unit of product (FU_{Bottle}).

Table 7. Anthropogenic GHG emissions (CF) assessed via LCA from the vineyard to the bottle of wine.

Life cycle phase			Mg CO_2eq per ha	kg CO_2eq per bottle (0,75L)
Agricultural phase	Diesel for farming	Fuel production and consumption for field operations	0,23	0,12
	Raw materials	Plant protection products (copper oxide, sulphur)	0,01	0,003
		Yarns for binding (iron, pvc)	0,004	0,002
	Packaging of raw materials	Packaging of protection products (paper)	0,0001	0,00004
	Transport[1]	Transport of raw materials	0,002	0,001
	Total sustainable cultivation and management of the vineyard (15%)		**0,24±0,05**	**0,12±0,03**
Transformation process	Raw materials	Yeast, nutrients, sulphur dioxide, etc.	0,001	0,0004
	Packaging of raw materials	Packaging of raw materials (plastic, aluminum)	0,07	0,03
	Transport[1]	Transport of raw materials	0,0001	0,00004
	Electricity	IT energy mix	0,65	0,32
	Total vinification and bottling phase (39%)		***0,72±0,14***	***0,36±0,07***
	Primary packaging	Bottle	0,48	0,24
		Cork	0,01	0,01
		Cap seal	0,01	0,003
		Frontal and back label (recycled paper)	0,01	0,004
		Cardboard box containing 6 bottles	0,09	0,05
	Transport[1]	Transport of primary packaging	0,02	0,01
	Second and third packaging	Packaging for transport (plastic, paper)	0,001	0,001
	Total wine packaging (46%)		***0,61±0,12***	***0,31±0,06***
	Total transformation process in the cellar (85%)		**1,33±0,27**	**0,67±0,14**
Total CF			**1,57±0,27**	**0,79±0,14**

Note: uncertainties values are derived assuming an average uncertainty of 20% of the data used for the LCA.

[1] The GHG emissions from the transport has been based on the distance travelled and the load of the truck including an empty return trip.

4.4 Combined analysis for a comprehensive greenhouse gas budget

The diverse components of the GHG budget of the overall wine making process (assessed with Eq. 1) are considered in this section in relation to the agricultural phase in the field and to the transformation process in the cellar. In particular, all the GHG emissions and removals occurring in the field are considered, including both the (a) biogenic and (b) anthropogenic GHG emissions generated for the grape production and the (c) carbon sink function of the vineyard. Then, for a complete assessment of the full grape-to-wine system, also the (d) GHG emissions generated by the grape transformation process into wine are evaluated (Figure 3).

As previously reported, the main contribution in terms of uptake of carbon from the atmosphere is provided by the biogenic CO_2 vineyard–atmosphere fluxes measured with the EC technique, that registered an average net annual sink of 5,5±0,05 Mg CO_2 ha^{-1} $year^{-1}$ in 2014-2015 ($F_{CO2(EC)}$, see Table 8). As discussed in section 4.1, these results confirm the role of the vineyard system of carbon sink thanks to its aptitude to sequester carbon in the permanent woody structures and in the soil enhanced by the sustainable agronomic practices of no-till and the presence of grass cover applied in the field (Gianelle et al., 2015; Longbottom and Petrie 2015; Marras et al., 2015). These findings demonstrate the positive effect of such sustainable practice that revealed to be able to increase the carbon sink of the vineyard, thus contributing to climate change mitigation.

Nevertheless, this positive budget in terms of carbon sink is reduced by the annual carbon stock change due to the grape harvest and the pruning of biomass that is shredded and removed from the vineyard as a strategy to avoid the spread of pests and diseases thus strongly reducing the use of chemicals for pests control. The amount of carbon removed by the grape harvest and the pruning of biomass corresponded respectively to 1,23±0,25 and 2,88±0,7 Mg CO_2eq ha^{-1} $year^{-1}$ (F_G and F_{PB} in Table 8). However, the vineyard resides (pruned biomass + grapefruit resides) are collected for the production of compost to be used on-farm as organic fertilizer of soil. In this way the carbon subtracted with the removal of grape and pruned biomass is then in part reallocated to the vineyard system through the compost application to soil. The amount of carbon that is assumed to be reallocated to the soil corresponds to 0,99±0,4 Mg CO_2eq ha^{-1} $year^{-1}$ (F_S in Table 8), at the net of the CO_2, CH_4 and N_2O generated by the compost fermentation that accounted for a total GHG emission of 1,96±0,5 Mg CO_2eq ha^{-1} $year^{-1}$ (sum of $F_{CO2(C)}$, $F_{CH4(C)}$ and $F_{N2O(C)}$ in Table 8) and of the CO_2 soil respiration following the compost application already included in the EC measures. For a comprehensive assessment also the final N_2O emissions from the soil due to the compost application has been subtracted to the total GHG budget, corresponding to 0,15±0,02 Mg CO_2eq ha^{-1} $year^{-1}$ ($F_{N2O(S)}$ in Table 8).

Thus, if only including the (a) biogenic GHG fluxes (F_{BIOG}) of -3,39±0,71 Mg CO_2eq ha^{-1} $year^{-1}$ and the (c) carbon stock changes due to the agronomic management (F_{MG}) of 3,12±0,85 Mg CO_2eq ha^{-1} $year^{-1}$, the GHG budget of the sustainable vineyard system results to be a positive sink of carbon equivalent to 0,27±1,11 Mg CO_2eq ha^{-1} $year^{-1}$ that can be considered as the potential carbon sink of a unit of land (hectare) of a sustainable managed vineyard (Figure 3). This positive result in term of carbon sink is mainly due to sustainable practices such as the no-till and grass cover in the vineyard and the application of compost derived by the vineyard residues, that lead to a significant increase in carbon sequestration by the system. Therefore, these findings shows as sustainable viticulture can be a low-carbon agriculture with a potential to even contribute to climate change mitigation in terms of carbon sink with a contribution per unit of managed land of 0,27±1,11 Mg CO_2eq ha^{-1} year^{-1}.

Moreover, if considering also the (b) anthropogenic GHG emissions coming from the field operations for the sustainable management of the vineyard, that accounted for 0,24±0,05 Mg CO_2eq ha^{-1} year^{-1} (E_{Field} in Table 8), the overall GHG budget at the vineyard level tends to be close to zero (Figure 3), showing a potential carbon neutrality of sustainable viticulture.

The sustainable transformation process (including vinification, bottling and packaging) still remains a source of GHG emissions (d) of 1,33±0,27 Mg CO_2eq ha^{-1} year^{-1} (Figure 3), albeit sensibly reduced respect to average values in literature.

However, it should be noticed that, as discussed in section 4.3, the sustainable management of the vineyard leads to a general low contribution to climate change in terms of anthropogenic GHG emissions per hectare or per bottle of wine. This is mainly due to a minor use of inputs, with particular regard to the use of agrochemical compounds for fertilization and plant protection. The lower contribution to climate change in terms of anthropogenic GHG emissions occurs also in the transformation process in the cellar. The reduced use of energy for electricity thanks to the natural cooling of the cellar that is dug into the rock and the use of ultralight glass bottle with 10% of glass less than conventional wine bottles result in minor GHG emissions per hectare or per bottle of wine.

Therefore, this study shows that sustainable viticulture and wine making process have in general a lower contribution to climate change in terms of anthropogenic GHG emissions per hectare or per bottle of wine. Moreover the results demonstrate also that sustainable viticulture is a low-carbon agriculture that can turn the system into a net carbon sink able to totally compensate anthropogenic GHG emissions generate from the field (Figure 3), allowing food production with a potential carbon neutrality without contributing to exacerbate climate change.

Hence, sustainable viticulture can lead to beneficial effects to climate change both in terms of enhanced capacity to capture carbon from the atmosphere and in terms of reduced anthropogenic GHG emissions for the management, while ensuring food production. The overall benefit of sustainable managed viticulture systems demonstrated in this study is related to the capacity to be a positive carbon sink so to even compensate the anthropogenic GHG emissions generated from the field operations, leading to a carbon neutral agrosystem.

Table 8. Annual GHG budget of the wine production. Positive sign (+) represents an emission and negative sign (-) represents a sink.

	GHG budget (GHG_W)		**Method for the assessment**	**Mg CO_2eq per hectare**	**kg CO_2eq per bottle**
(a)	**Biogenic fluxes of GHGs in the vineyard:**				
	CO_2 fluxes	$F_{CO2(EC)}$	EC technique	-5,50±0,5	-2,75±0,3
	CO_2 from compost production	$F_{CO2(C)}$	IPCC (2006)	1,25±0,1	0,62±0,05
	CH_4 from compost production	$F_{CH4(C)}$	IPCC (2006)	0,45±0,4	0,23±0,2
	N_2O from compost production	$F_{N2O(C)}$	IPCC (2006)	0,26±0,29	0,13±0,15
	N_2O from soil management	$F_{N2O(S)}$	IPCC (2006)	0,15±0,02	0,07±0,01
	Total F_{BIOG}			**-3,39±0,71**	**-1,7±0,36**
(c)	**Carbon stock changes due to the agronomic management:**				
	SOC stock change from compost application	F_S	Data from literature	-0,99±0,44	-0,5±0,2
	Carbon loss due to the grape harvest	F_G	Direct measure	1,23±0,25	0,62±0,13
	Carbon loss due to the pruning of biomass	F_{PB}	Direct measure	2,88±0,71	1,44±0,35
	Total F_{MG}			**3,12±0,85**	**1,56±0,43**
	Anthropogenic GHG emissions:				
(b)	GHG emissions from the field operations	E_{Field}	LCA	0,24±0,05	0,12±0,03
(d)	GHG emissions from the transformation	E_{Cellar}	LCA	1,33±0,27	0,57±0,14
	Total E_{ANTR}			**1,57±0,27**	**0,79±0,14**
	Total GHG_W			**1,30±1,14**	**0,65±0,57**

5. Conclusion

Sustainable agriculture is recognized as the pathway to address climate change adaptation and mitigation while ensuring food production to feed the current human population and the expected 9.8 billion by 2050 (FAO 2017; UN, 2017). The study shows that sustainable agricultural practices applied to viticulture lead to a low-carbon agrosystem, with a lower contribution to climate change in terms of GHG emissions per hectare (or per bottle). The minor use of inputs, with particular regard to the use of agrochemical compounds for fertilization and plant protection, the reduced use of energy for electricity in the cellar and the use of ultralight glass bottle make the wine making process sustainable with lower GHG emissions.

On the other side, vineyard systems could act as carbon sink thanks to their aptitude to sequester carbon in their permanent woody structures and in soils, enhanced by practices as no-till and the presence of grass cover. Also the application of compost obtained from vineyard residues in substitution of the use of synthetic fertilizers reduces the use of inputs and related GHG emissions, contributing to climate change mitigation, with a significant increase in soil carbon sequestration.

These findings confirm the positive effect of sustainable practices applied to viticulture and highlight their potential to even turn the agrosystem into a net carbon sink able to totally compensate anthropogenic GHG emissions generate for the field management. The overall GHG balance of the agricultural phase resulted to be a such positive carbon sink so to even compensate the anthropogenic GHG emissions generated from the field operations, leading to a carbon neutral agrosystem, thereby contributing to climate change mitigation. The sustainable transformation process still remain a source of GHG emissions, albeit sensibly reduced respect to average values in literature.

A such kind of assessment of the GHG budget of sustainable viticulture can provide also useful information for the monitoring of the effect on climate change of sustainable practices applied for example in the framework of national adaptation or mitigation plans and in the context of the CAP. Moreover, the assessment on GHG budget of viticulture provided in this study is useful also for the reporting and accounting of emissions and removals in the LULUCF and agriculture sectors in the framework of the UNFCCC and the second commitment period of the Kyoto Protocol (2014-2020) as well as under the commitments foreseen by the Reg. UE 529/2013 for the reporting of emissions and removals of cropland management.

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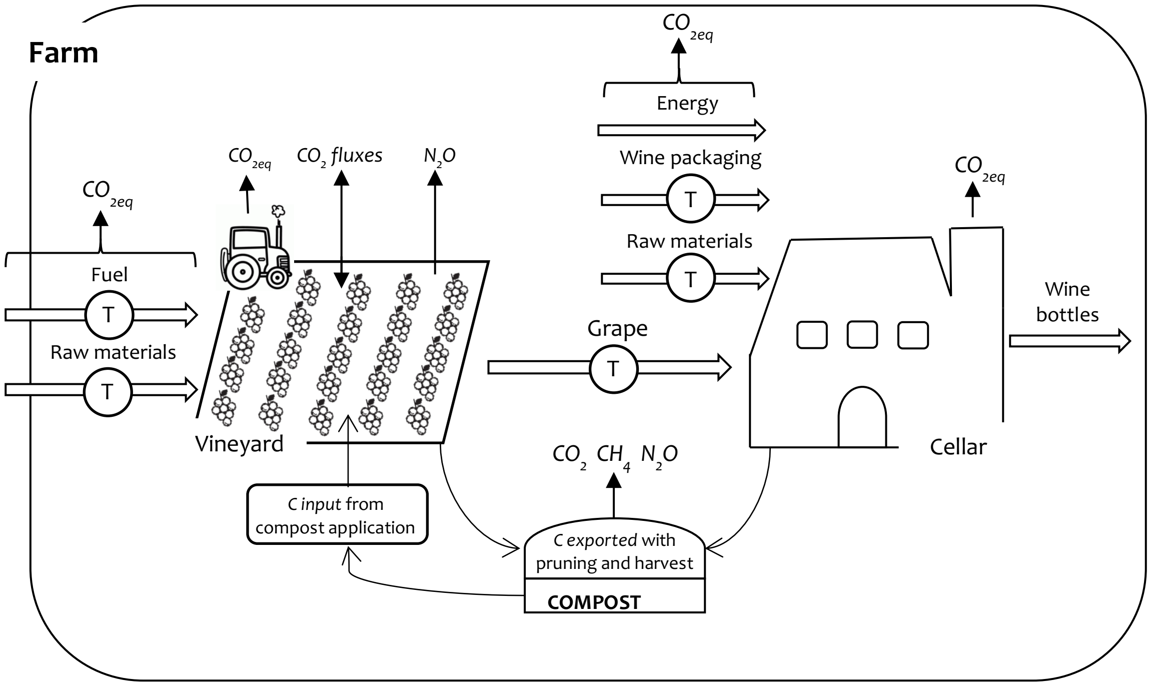

Figure 1. Breakdown of the components contributing to the total GHG budget at farm level

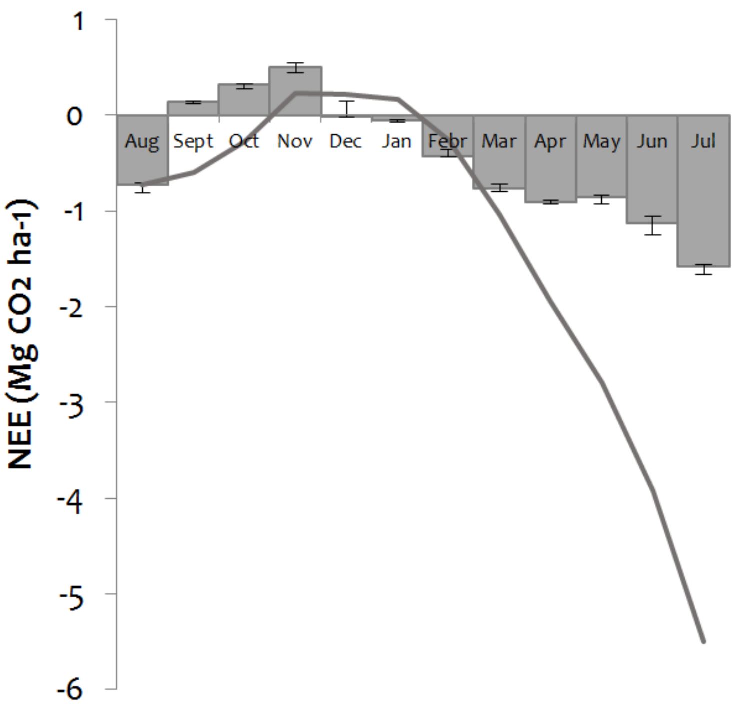

Figure 2. Monthly vineyard–atmosphere net ecosystem exchange (NEE) of biogenic fluxes of CO_2 measured with Eddy Covariance technique (Mg CO_2 ha^{-1}). Positive (+) sign indicates an emission while negative (-) sign indicates a sink. The vertical bars indicate the distribution between the 5^{th} and the 95^{th} percentile. The continuous line shows the carbon accumulation (expressed in Mg CO_2 ha^{-1}) as sum of the monthly fluxes.

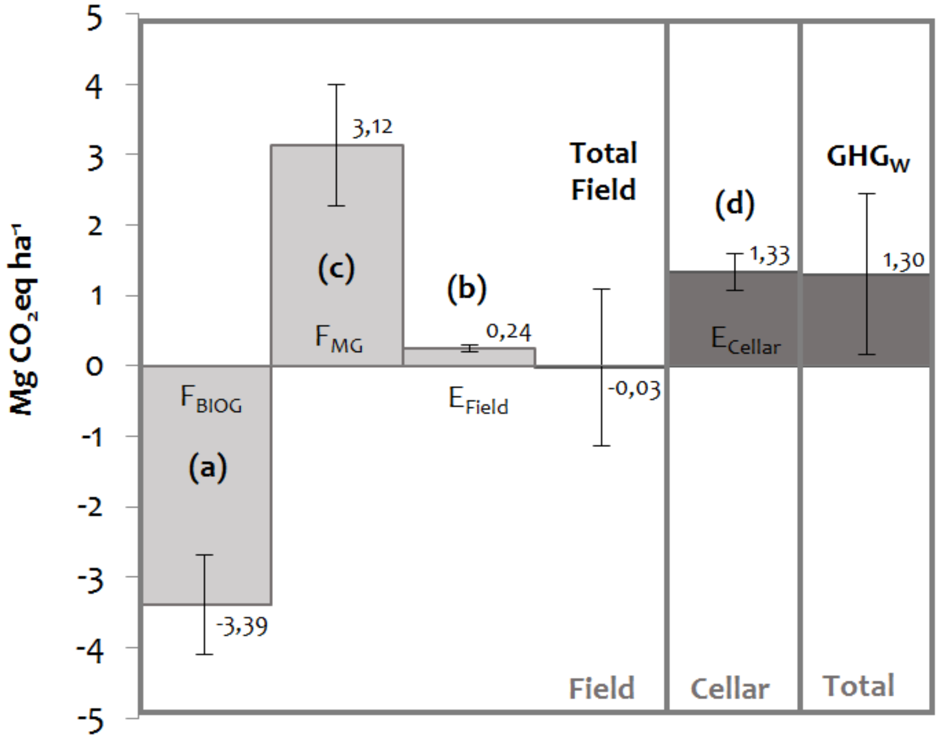

Figure 3. The GHG budget from the vineyard system up to the wine production (GHG_W), calculated as the sum of the (a) biogenic vineyard–atmosphere fluxes of greenhouse gases (F_{BIOG}), the (c) annual carbon stock changes in the vineyard due to the agronomic operations in the field (F_{MG}), and the (b + d) anthropogenic emissions of greenhouse gases due to the management of the overall life cycle from the vineyard to the bottle of wine (E_{Field} and E_{Cellar}). Positive (+) sign indicates an emissions into the atmosphere, while a negative (-) sign represents an uptake from the atmosphere. The vertical bars indicate the uncertainty range.