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1 Carbon Footprint assessment on a mature vineyard

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# 13 Abstract

14 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

16 terms of production and distribution worldwide. However, agriculture can also contribute to

17 sequester carbon, so it is important to understand the double role of such systems.

18 Even if the agricultural phase is recognized by several authors to have a strong environmental

19 impact during the wine production, only a few studies estimate GHG emissions related to this stage.

20 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.

24 The main goal of this work was to determine the CF of a mature vineyard during the grape

25 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

27 "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  $CO_2$ 

30 exchange over the vineyard and the net  $CO_2$  budget was computed by combining the measured

31 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  $0.39 \text{ kg CO}_2$ -eq and most of them derived from external inputs such as fossil fuel

34 combustion and soil management.

35	In addition, ecophysiological processes could contribute to offset the CO <sub>2</sub> emissions released during
36	the agronomic practices.

- 37
- 38
- 39 Keywords:

40 Carbon balance; Agricultural phase; Grape; Eddy Covariance; GHG emissions; Vineyard

- 41 management
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# 48 **1 Introduction**

In recent years, there has been a growing concern related to the eco-sustainability of production

50 processes, and consumers are becoming more interested in environmentally friendly practices,

51 products, and services. The widespread adoption of intensive production systems in agriculture

52 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

54 sustainable production processes.

55 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

57 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

60 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

62 impact of these data makes necessary the development of methodologies aiming to estimate

63 greenhouse gases (GHGs) emitted in the atmosphere from everyday products and services, and to

64 search for useful strategies to reduce them.

Life Cycle Thinking (LCT) is a quantitative approach which aims at taking into account all life

66 cycle phases of a product (e.g. extraction of the raw materials, pre-production processes,

67 production, consumption, end-of-life) in a broad range of methodologies and instruments for

68 sustainability assessment and management. Several LCT-based methods have already been

- 69 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
- <sup>73</sup> 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
- vater footprint or carbon footprint (CF) (Čuček et al., 2012; Laurent et al., 2012; Scipioni et al.,
- 76 2012).
- CF analysis, as a part of the LCA approach, quantifies CO<sub>2</sub> 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
- 82 considering its Global Warming Potential (GWP).
- 83 Recently, several approaches and guidelines have been developed for accounting GHG emissions,
- 84 including (1) methodologies at territorial scale developed by the IPCC, (2) the Publicly Available
- 85 Specification 2050 (PAS 2050) developed by the British Standard Institute and the Carbon Trust
- 86 (BSI, 2011), and the (3) Greenhouse Gas Protocol (GHG-Protocol) developed by the World
- 87 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
- 89 French Bilan Carbone (ADEME, 2010), and the OIV-GreenHouse Gas Accounting Protocol (OIV-
- 90 GHGAP).
- 91 Winemaking process can be subdivided into two main phases: agricultural and industrial.
- 92 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).
- 95 Several studies applied the LCA methodology to evaluate the environmental performance of the
- 96 wine sector (Notarnicola et al., 2003; Aranda et al., 2005; Ardente et al., 2006; Petti et al. 2006;
- 97 Pizzigallo et al., 2008; Gazulla et al., 2010; Point et al., 2012; Vázquez-Rowe et al., 2012a,b;
- 98 Benedetto 2013; Neto et al., 2013), and the CF analysis (Colman and Paster 2007; Smyth and
- 99 Russell 2009; Cholette and Venkat 2009; CSWA 2009; Smart et al., 2009; Bosco et al., 2011;
- 100 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).
- 104 In the winemaking process, the agricultural phase has been recognized to contribute from 17%
- 105 (Rugani et al., 2013) up to 40% (Benedetto, 2013; Neto et al., 2013) to GHG emissions. Studies
- 106 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;
- 108 Bosco et al., 2011; Point et al., 2012; Benedetto 2013; Rugani et al., 2013; Fusi et al., 2014).
- 109 However, the determination of the CF in the agricultural phase is not a simple task because of
- 110 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 quantificationof this stage.
- 114 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
- 120 estimates and only part of them uses experimental data.
- 121 Micrometeorological methods are commonly applied to directly measure CO<sub>2</sub> 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
- 124 commonly used to obtain long-term measurements of CO<sub>2</sub> 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
- 127 known about the vineyard ability to sequester carbon and offset GHG emissions. CO<sub>2</sub> 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).
- 130 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
- 134 net carbon budget . The analysis was conducted in a typical Mediterranean vineyard. The IWCP
- 135 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.

#### 138 2 Materials and Methods

139

#### 140 *2.1 Carbon Footprint methodology*

The CF analysis was carried out in an experimental site located in the South of Sardinia (Italy). It 141 was performed using one kg of grape yield as functional unit, and identifying a system boundary 142 "from cradle to gate", excluding winemaking processes, distribution, and consumption. The 143 analysis focused on the main agricultural practices conducted in the period October 2009-144 September 2010: fertilization application, soil management tillage, pruning, and harvesting. 145 The CF was computed following the International Wine Carbon Protocol (IWCP), and adopting its 146 related calculator named International Wine Carbon Calculator (IWCC). In this work, only 147 emissions related to Scope 1 or "primary footprint" (i.e. all emissions under the direct control of the 148 farm) were considered and limited to the agricultural phase. Specifically, these are emissions related 149 to the use of fossil fuel, both for agronomic practices and for travelling from the farm center to the 150 field, and emissions from activities affecting the short-term carbon cycle (e.g. pruning, harvesting, 151 and human metabolism of workers). All GHG emissions are expressed as CO<sub>2</sub> amount (kg) when 152 carbon was directly released by the analyzed process or as CO<sub>2</sub>-eq (kg) when Nitrogen (N) 153 emissions were included, as requested by the CF guidelines. 154 Emissions from stationary fuel use (water heaters and frost fighting equipment), and fugitive 155 emissions are not considered since heaters or boilers are not used in the investigated farm. Also, 156 emissions from waste disposal are omitted because the amount is not significantly relevant as well 157

as emissions due to energy consumption for water application, which is produced outside the farmboundaries.

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

162

#### 163 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).

- 168 Direct CO<sub>2</sub> emissions related to fossil fuel (diesel) consumed for agronomic practices were
- 169 calculated based on the fuel quantity method of the IWCC by using an emission factor of 74.01 kg
- 170  $CO_2 GJ^{-1}$ . 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.  $108 \text{ km y}^{-1}$ ).

- An emission factor of 2.745 kg  $CO_2 l^{-1}$  diesel (IWCP) was used to estimate carbon emissions due to travels.
- 174 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
- 176 fertilizer, while emissions from managed soil were estimated using a factor of 3, following the
- 177 IWCP. Differences in land cover and soil composition are not considered in this calculation.
- 178 Pesticide emissions were not calculated since a few amount (4-7 kg ha<sup>-1</sup>) of a Sulphur compound is
- applied per year, and it was considered negligible (Fusi et al., 2014).
- 180 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<sup>-1</sup>, which is considered
- totally released into the atmosphere during the year. The N content (% N kg<sup>-1</sup> dry matter) in crop
- residues was estimated using the emission factor (0.25) suggested by Alfano et al. (2011) and then
- converted in CO<sub>2</sub>-eq emissions using the 310 Global Warming Potential factor (100 years time

185 horizon) (IPCC, 1995).

- 186 Carbon dioxide emissions related to grape production were calculated in a different way for grape
- 187 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
- 190 components, while a value of 2.06% (Baraldi et al., 2010) was used to estimate the N content.
- 191 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
- 193 (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<sup>-1</sup> was used to estimate total emissions from
- human respiration (http://www.engineeringtoolbox.com/co2-persons-d\_691.html).
- 196 197

#### 198 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
- 209 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
- 211 atmospheric science convention.
- Ecosystem emissions due to respiration processes (Reco), as well as Gross Primary Productivity
- 213 (GPP) were estimated with the marginal distribution sampling method (MDS) (Reichstein et al.,
- 214 2005), implemented in <u>http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/</u> (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.
- 219 Meteorological and radiometric stations were also placed in the site to measure the main
- 220 meteorological variables and the radiation balance components, respectively. Air temperature (Tair,
- °C), relative humidity (RH, %), precipitation (Pcp, mm), photosynthetically active radiation (PAR,
- $\mu$ mol quanta m<sup>-2</sup> s<sup>-1</sup>), and incoming and outcoming solar radiation (W m<sup>-2</sup>) 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.
- 227 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
- 230 line with those reported in the literature (slope = 0.76; R<sup>2</sup> = 0.86), so the measurements accuracy 231 was considered acceptable.
- 232
- 233 *2.3 Experimental site*
- The study was conducted in a typical Mediterranean vineyard located in the South of Sardinia, Italy
- 235 (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.

240

#### 241 **3 Results and Discussion**

242

## 243 *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).

251

#### 252 *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 255 application) and emissions due to soil management totaled 0.26 kg CO<sub>2</sub>-eq kg<sup>-1</sup>. The main processes 256 affecting the global carbon budget, expressed in terms of GWP impact during the grape production 257 phase, were represented by diesel consumption (both for field practices and travels), with 0.12 kg 258  $CO_2$  kg<sup>-1</sup>, and N released by the managed soil (0.13 kg  $CO_2$ -eq kg<sup>-1</sup>). These two inputs are 259 responsible for more than 90% to the total GHG emissions (Fig. 2). On average, diesel consumption 260 covered 44% of the GWP impact, while emissions from managed soil accounted for 50%. 261 This analysis showed that fossil fuels and soil tillaging are the two main emission sources, but 262 having a different impact on the global carbon budget. Soil tillaging affects the N emissions and the 263 organic carbon stored into the soil (i.e. roots, pruning, litter residues), characterized by a relatively 264 fast turnover (it is assumed that woody debris are respired away in about a year). On the other hand, 265 fuel affects the global carbon reservoirs representing an additional source of CO<sub>2</sub> emissions. Similar 266 267 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 268 from soil management (20-30%) was observed by Bosco et al. (2011) in Tuscany (Italy). Most of 269 studies in the literature, however, agreed that the amount of consumed diesel and N content should 270

- be revised to guarantee a net improvement in environmental impacts reduction (Neto et al., 2013;
- 272 Vázquez-Rowe et al., 2012b).
- 273 The impact of fertilization application is lower than the two previous inputs, contributing for about
- 5% (0.01 kg CO<sub>2</sub>-eq kg<sup>-1</sup>) to the global C budget. This value is in line with what reported in Spain
- 275 (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).
- 280 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
- $0.39 \text{ kg CO}_2$ -eq kg<sup>-1</sup>. 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.
- 286 CO<sub>2</sub>-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
- 289 (Bosco et al., 2011), 0.50 (Gazulla et al., 2010) and 0.80 kg CO<sub>2</sub>-eq (Point et al., 2012) during the
- agricultural phase. It should be noted that, in each study, differences in vineyard management and
- 291 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 inreleasing 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.
- 296

#### 297 *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
- 305 measured fluxes is challenging.
- 306 The average Net Ecosystem Exchange (NEE) measured by the Eddy Covariance at the experimental
- site was -0.53 g C m<sup>-2</sup> day<sup>-1</sup>. The maximum daily carbon sequestration occurred on 25 July 2010 (-
- $5.58 \text{ g C m}^{-2} \text{ day}^{-1}$ ), while the maximum C loss was registered on 22 April 2010 (5.07 g C m<sup>-2</sup> day<sup>-1</sup>)
- <sup>1</sup>), mainly due to soil tillage practices. Data related to the carbon budget at monthly scale are
- 310 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  $-108 \text{ g C m}^{-2}$ , respectively), while C emissions (Reco) ranged from 76 g C m<sup>-2</sup> (September)
- 314 to 134 g C m<sup>-2</sup> (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<sup>-1</sup> as reported by Guo et al. (2014), or forest sites
- 321 (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
- 323 (Zenone et al., 2013), showing that the vineyard could play a role in sequestering C. In terms of
- 324 CO<sub>2</sub>, our vineyard was able to annually sequester 715.05 g CO<sub>2</sub> m<sup>-2</sup>.
- 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.
- 332

# 333 *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:
- 350

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

and results showed an annual carbon sequestration equal to  $0.24 \text{ kg CO}_2 \text{ kg}^{-1}$ . 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<sub>2</sub> 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<sub>2</sub>) 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<sub>2</sub> 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:
- 365

366

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

367

The agricultural phase is then characterized by a net carbon release of  $0.036 \text{ kg CO}_2$ -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

(2)

external inputs by sequestering  $0.124 \text{ kg CO}_2$ -eq kg<sup>-1</sup>.

#### 374 4 Conclusions

375 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

378 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 383 practices and results showed that emissions both from external inputs and biogenic components 384 amounted to 0.39 kg  $CO_2$ -eq per kg of grape yield. In addition, the main terms responsible for  $CO_2$ 385 emissions in the atmosphere are external inputs (such as the fossil fuel combustion) and soil tillage. 386 These results are in accordance with findings in the literature. Since farmer already reduced the 387 388 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 389 will not probably determine a significant improvement. A solution to reduce the global warming 390 impact resulting from the use of agricultural machinery could be found in reducing soil tillage 391 392 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<sub>2</sub> per kg of grape yield. Further, the plants were able to grow of about 0.12 kg of dry matter per plant.

397 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
- 400 tower. The agricultural phase of the wine production process was, in fact, responsible for about
- 401 0.036 kg CO<sub>2</sub>-eq emissions per kg of grape yield, but this trend could be opposite (i.e. the vineyard
- 402 could sequester  $0.124 \text{ kg CO}_2$ -eq kg<sup>-1</sup>) depending on the fraction of fuel and human respiration
- 403 emissions included into the Eddy Covariance measured NEE.

404 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 potentialenvironmental implications.

407

#### 408

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- 419

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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<sub>2</sub>-eq kg<sup>-1</sup> of grape yield, expressed in %
unit) during the grape production phase.



Fig. 3. Monthly variation in measured carbon fluxes (g C m<sup>-2</sup> month<sup>-1</sup>). GPP = Gross Primary Productivity; Reco = ecosystem respiration; NEE = Net Ecosystem Exchange.

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

հ	n	C
υ	U	-

	Direct CO <sub>2</sub> emissions	kg kg <sup>-1</sup>
A	Fuel consumption for field practices	0.1056
В	Fuel consumption for travels	0.0100
С	Human work	0.0043
D	Crop residues	0.1289
E	Grape yield	0.4783
	Indirect CO <sub>2</sub> emissions (from N)	
F	Fertilization application	0.0130
G	Soil management	0.1320
Η	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	