

Carbon footprint assessment on a mature vineyard

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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)  
15 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  
21 CO<sub>2</sub> emissions caused by a production process) of the agricultural phase is not a simple task due to  
22 the large uncertainty related to local characteristics, climate, land, agricultural practices, grape type,  
23 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  
26 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,  
28 the study was addressed to assess the role of the vineyard to offset carbon emissions at the end of  
29 the productive year. The Eddy Covariance technique was used to directly measure the CO<sub>2</sub>  
30 exchange over the vineyard and the net CO<sub>2</sub> budget was computed by combining the measured  
31 fluxes and the GHG emissions estimated by the CF analysis.

32 Results showed that the production of one kg of grape determined a total amount of GHG  
33 emissions of 0.39 kg CO<sub>2</sub>-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**

49 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,  
53 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  
56 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  
58 and Wine (OIV) states that, in 2014, 270 million hectoliters of wine have been produced on a total  
59 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  
61 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.

65 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  
70 environmental burdens associated with the different life cycle stages of wine (Petti et al., 2010;  
71 Neto et al., 2013; Vázquez-Rowe et al., 2013), and providing multiple impact categories to be  
72 analyzed (e.g. global warming, human and environmental toxicity, natural resource depletion, ozone  
73 layer depletion, summer smog) However, LCA also presents disadvantages due to its holistic and  
74 comprehensive principles. Consequently, LCA studies developed a number of indicators, such as  
75 water footprint or carbon footprint (CF) (Čuček et al., 2012; Laurent et al., 2012; Scipioni et al.,  
76 2012).

77 CF analysis, as a part of the LCA approach, quantifies CO<sub>2</sub> emissions directly and indirectly caused  
78 by an activity or accumulated during the lifecycle of a product or service (Wiedmann and Minks,  
79 2007). This approach enables to identify the contribution of a production process to climate change  
80 considering emissions of the GHGs covered by the Kyoto Protocol (Bosco et al., 2011). It is  
81 typically expressed in kg CO<sub>2</sub>-equivalent (CO<sub>2</sub>-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).  
88 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-  
93 production and grape production sub-phases, while the industrial phase includes vinification,  
94 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  
101 analyzed the CF for a single stage of the production process by addressing specific aspects related  
102 to it as, for example, the agricultural phase (Kavargiris et al, 2009; Venkat, 2012), the wine

103 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

107 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,

111 climate conditions, land texture, agricultural practices, and grape varieties (Rugani et al., 2013). In

112 addition, a general lack of experimental data and information makes difficult the CF quantification

113 of this stage.

114 Apart from the production system complexity, a critical point is to include, in the net carbon budget

115 estimation, the carbon sequestered by the different components (soil and grass cover, woody

116 biomass, etc.) of the vineyard system (OIV, 2011) that can offset the emissions from fossil fuel,

117 usually representing the larger source of GHG in the agricultural systems. Most of studies assume

118 balance between the biogenic CO<sub>2</sub> sequestered and released back to the atmosphere. As a result, CF

119 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

122 system and the lower atmosphere, and the Eddy Covariance (EC) technique is the standard

123 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

125 and quantifying ecosystems capacity to absorb atmospheric carbon.

126 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

128 measurements over vineyards were usually reported for short measurement periods (a few weeks up

129 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

131 during the agricultural phase of the production process. In addition, the research tried to identify the

132 agronomic practices that mainly contributed to emissions, affecting the global carbon budget, and to

133 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

136 studied vineyard to directly measure the CO<sub>2</sub> flux in the soil-vegetation-atmosphere continuum.



## 138 **2 Materials and Methods**

139

### 140 *2.1 Carbon Footprint methodology*

141 The CF analysis was carried out in an experimental site located in the South of Sardinia (Italy). It  
142 was performed using one kg of grape yield as functional unit, and identifying a system boundary  
143 “from cradle to gate”, excluding winemaking processes, distribution, and consumption. The  
144 analysis focused on the main agricultural practices conducted in the period October 2009-  
145 September 2010: fertilization application, soil management tillage, pruning, and harvesting.  
146 The CF was computed following the International Wine Carbon Protocol (IWCP), and adopting its  
147 related calculator named International Wine Carbon Calculator (IWCC). In this work, only  
148 emissions related to Scope 1 or “primary footprint” (i.e. all emissions under the direct control of the  
149 farm) were considered and limited to the agricultural phase. Specifically, these are emissions related  
150 to the use of fossil fuel, both for agronomic practices and for travelling from the farm center to the  
151 field, and emissions from activities affecting the short-term carbon cycle (e.g. pruning, harvesting,  
152 and human metabolism of workers). All GHG emissions are expressed as CO<sub>2</sub> amount (kg) when  
153 carbon was directly released by the analyzed process or as CO<sub>2</sub>-eq (kg) when Nitrogen (N)  
154 emissions were included, as requested by the CF guidelines.

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

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

162

#### 163 *2.1.1 Calculation methodology*

164 The analysis was performed through the IWCC. However, since the use of this calculator seems to  
165 overestimate the CF calculated with other LCA softwares (Rugani et al., 2013), GHG emissions  
166 related to some terms were calculated using data directly collected by the authors through specific  
167 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<sub>2</sub> GJ<sup>-1</sup>. Fuel consumption due to travels was calculated considering the IWCC travel distance  
171 method. Travel distance was 6 km per round-trip for a total of 18 times per year (i.e. 108 km y<sup>-1</sup>).

172 An emission factor of 2.745 kg CO<sub>2</sub> l<sup>-1</sup> diesel (IWCP) was used to estimate carbon emissions due to  
173 travels.

174 In the experimental site, organic and chemical fertilizers, with a N content of 2% and 9%,  
175 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  
179 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  
181 was collected and desiccated to estimate an amount of 1289.2 kg CO<sub>2</sub> ha<sup>-1</sup>, which is considered  
182 totally released into the atmosphere during the year. The N content (% N kg<sup>-1</sup> dry matter) in crop  
183 residues was estimated using the emission factor (0.25) suggested by Alfano et al. (2011) and then  
184 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  
188 used to calculate the CO<sub>2</sub> content in the grape juice. A moisture content of 80% on fresh weight  
189 (established as mean value from lab analysis) was used to calculate the CO<sub>2</sub> 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,  
192 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  
194 et al. (2012), an emission factor of 0.46 kg CO<sub>2</sub> h<sup>-1</sup> was used to estimate total emissions from  
195 human respiration ([http://www.engineeringtoolbox.com/co2-persons-d\\_691.html](http://www.engineeringtoolbox.com/co2-persons-d_691.html)).

196

197

## 198 *2.2 Micrometeorological measurements*

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



205 Eddy Covariance data were acquired at 10 Hz and averaged every 30 minutes. Raw data were  
206 processed using the EddyPro v. 4.2.1 software developed by Li-Cor Biosciences. The amount of  
207 data removed by quality check was 18% over the period (October 2009-September 2010).

208 Net ecosystem exchange (NEE) is the net CO<sub>2</sub> exchange with the atmosphere directly measured  
209 with the EC technique. Positive NEE values represent net carbon (C) emissions to the atmosphere  
210 and negative values represent the C amount sequestered from the atmosphere, according to the  
211 atmospheric science convention.

212 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 <http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/> (2013 version). The  
215 online tool was also used to fill gaps in the dataset.

216 Four heat flux plates (mod. HFP01SC, Hukseflux, Delft, NL) were located, along a transect  
217 between rows, at -0.07 m soil depth to have a representative measure of soil heat flux (G). Soil  
218 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 (T<sub>air</sub>,  
221 °C), relative humidity (RH, %), precipitation (P<sub>cp</sub>, mm), photosynthetically active radiation (PAR,  
222 μmol quanta m<sup>-2</sup> s<sup>-1</sup>), and incoming and outgoing solar radiation (W m<sup>-2</sup>) were measured. During  
223 the growing period, the Leaf Area Index (LAI) was also monitored by LAI-2000 (Li-cor, Lincoln,  
224 NE, USA) based on the principle of interception of the light radiation from vegetation. In addition,  
225 soil temperature and moisture were monitored at -0.20, -0.40, and -0.60 m depths in several  
226 vineyard locations.

227 The energy balance closure was used to evaluate the accuracy of measured data. In the literature,  
228 deviations of about 20-30% from closure are commonly observed in surface energy budget  
229 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*

234 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  
236 variety is Vermentino, which is trained in a Guyot system. The rows are oriented in east-west  
237 direction with 0.8 m between plants and 2.1 m between rows (5952 vines ha<sup>-1</sup>). Vegetation is about

238 2.0 m tall with 50% ground shading of the clay soil. The vineyard is irrigated during the dry season  
239 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*

244 Climate is typical of the Mediterranean area, with a mean annual temperature of 16.9 °C and mean  
245 annual precipitation of 484 mm. Annual precipitation measured at the site was 518 mm, mainly  
246 concentrated in spring and fall (Fig. 1a). Soil volumetric water content (SWC) ranged from 19% to  
247 30% during the year, with an average soil moisture value of about 25% (Fig. 1a). Mean annual  
248 temperature was 15.5 °C, slightly lower than climate mean. Daily mean temperature ranged from  
249 1.6 °C to 28.2 °C (Fig. 1b), with a minimum absolute value occurred in February 2010 (-1.2 °C)  
250 and a maximum in August 2010 (37.2 °C).

251

### 252 *3.2 Carbon footprint analysis*

253 Direct and indirect CO<sub>2</sub> (i.e. N converted into CO<sub>2</sub>-eq) emissions were quantified per each  
254 agronomic practice and results are reported in Table 2.

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

262 This analysis showed that fossil fuels and soil tillaging are the two main emission sources, but  
263 having a different impact on the global carbon budget. Soil tillaging affects the N emissions and the  
264 organic carbon stored into the soil (i.e. roots, pruning, litter residues), characterized by a relatively  
265 fast turnover (it is assumed that woody debris are respired away in about a year). On the other hand,  
266 fuel affects the global carbon reservoirs representing an additional source of CO<sub>2</sub> emissions. Similar  
267 results were found by other authors (Benedetto 2013; Fusi et al., 2014; Neto et al., 2013; Point et  
268 al., 2012; Venkat, 2012), while lower contribution for diesel consumption (20%) and N emissions  
269 from soil management (20-30%) was observed by Bosco et al. (2011) in Tuscany (Italy). Most of  
270 studies in the literature, however, agreed that the amount of consumed diesel and N content should

271 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  
274 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  
276 Point et al. (2012). However, differences in local climate conditions, grape variety, soil  
277 characteristics, and agricultural practices could explain the variability observed in the results from  
278 different studies (Rugani et al., 2013). Human work only contributed for about 2% to the global  
279 carbon budget (Fig. 2).

280 When considering emissions from both external inputs and biogenic components due to agronomic  
281 practices (i.e. crop residues), results from this study showed a total amount of GHG emissions of  
282 0.39 kg CO<sub>2</sub>-eq kg<sup>-1</sup>. Both emissions from fossil fuel and crop residues decomposition contributed  
283 for about 30%, even if the crop residues release carbon that was recently fixed, so having no direct  
284 influence on the global carbon budget.

285 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  
287 Vázquez-Rowe et al., (2012b). Other studies refer the CF results to the 0.75 l wine bottle as  
288 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  
290 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  
292 differences in the final results, but all contribute to understand the role played by vineyards in  
293 releasing GHG emissions.

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

296

### 297 *3.3 Micrometeorological measurements*

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

304 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  
307 site was  $-0.53 \text{ g C m}^{-2} \text{ day}^{-1}$ . The maximum daily carbon sequestration occurred on 25 July 2010 ( $-$   
308  $5.58 \text{ g C m}^{-2} \text{ day}^{-1}$ ), while the maximum C loss was registered on 22 April 2010 ( $5.07 \text{ g C m}^{-2} \text{ day}^{-1}$ ),  
309 mainly due to soil tillage practices. Data related to the carbon budget at monthly scale are  
310 presented in Fig. 3.

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

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

319 At annual scale, the vineyard was able to sequester  $195 \text{ g C m}^{-2}$ . This amount is lower if compared  
320 to other vineyard ecosystems, e.g.  $868 \text{ g C m}^{-2} \text{ y}^{-1}$  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  
322 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  $\text{CO}_2$ , our vineyard was able to annually sequester  $715.05 \text{ g CO}_2 \text{ m}^{-2}$ .

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

332

### 333 *3.4 Combined analysis for the net carbon budget calculation*

334 As observed by other authors (Soosay et al., 2012), agricultural phase may contribute up to 28% of  
335 carbon emissions due to the biogenic components (i.e. decomposing biomass, timber decay) and  
336 carbon sequestration linked to vine growth and sugar production in the grapes. Since the difficulty  
337 to have reliable measurements or estimates of these quantities (Bosco et al., 2011), most of the

338 studies assume that the amount of biogenic CO<sub>2</sub> sequestered from the atmosphere during vine and  
339 grape growth is equal to the amount of CO<sub>2</sub> released back to the atmosphere by the oxidation  
340 processes in pruning wastes and grapes (Neto et al., 2013) or they did not account for short-term  
341 processes (Pattara et al., 2012). As a result, CF analysis usually omits biogenic carbon issues, even  
342 if they have been taken up by CF guidelines (i.e. PAS 2050).

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

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

350

$$351 \text{ Biom} = \text{NEE} - E \quad (\text{kg CO}_2 \text{ kg}^{-1}) \quad (1)$$

352

353 and results showed an annual carbon sequestration equal to 0.24 kg CO<sub>2</sub> kg<sup>-1</sup>. In terms of biomass,  
354 this amount corresponds to about 0.12 kg of dry matter per plant. This quantity represents the  
355 annual plant growth observed during the year, and highlights that the amount of CO<sub>2</sub> sequestered  
356 and released in the short-term processes is not balanced and it should be taken into account in the  
357 final carbon budget calculation.

358 In this context, the final carbon cost (CC) of the grape production process was calculated as the  
359 difference between NEE and the emissions by both biogenic components (indirect CO<sub>2</sub>) and  
360 external inputs. It is needed to remind that turbulent flux (NEE) is strictly linked to the wind  
361 direction, wind intensity, and other conditions that may occur in the field. So, it is hard to relate the  
362 measured NEE with CO<sub>2</sub> emitted from external inputs, such as the fossil fuel (A) and human work  
363 (C). If the terms A and C are assumed to be completely missed by the EC measurements, the final  
364 carbon cost (CC) is calculated by adding these terms to the other emission sources as:

365

$$366 \text{ CC} = -\text{NEE} + \text{A} + \text{B} + \text{C} + \text{E} + \text{F} + \text{G} + \text{H} + \text{I} \quad \text{kg CO}_2\text{-eq kg}^{-1} \quad (2)$$

367

368 The agricultural phase is then characterized by a net carbon release of 0.036 kg CO<sub>2</sub>-eq per kg of  
369 grape. However, it is reasonable to also assume that the EC tower is able to include A and C  
370 emissions in the measured flux. In this case, the vineyard is able to offset GHG emissions due to the  
371 external inputs by sequestering 0.124 kg CO<sub>2</sub>-eq kg<sup>-1</sup>.

372

373

#### 374 **4 Conclusions**

375 The Carbon Footprint analysis was conducted in a mature vineyard located in the South of Sardinia  
376 (Italy), and coupled with direct measurements of CO<sub>2</sub> fluxes through the Eddy Covariance  
377 technique, with the aim to quantify the global warming impact of the agricultural phase during a  
378 productive year.

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

383 The Carbon Footprint analysis allowed to quantify the GHG emissions related to agronomic  
384 practices and results showed that emissions both from external inputs and biogenic components  
385 amounted to 0.39 kg CO<sub>2</sub>-eq per kg of grape yield. In addition, the main terms responsible for CO<sub>2</sub>  
386 emissions in the atmosphere are external inputs (such as the fossil fuel combustion) and soil tillage.  
387 These results are in accordance with findings in the literature. Since farmer already reduced the  
388 amount of applied fertilizers, this practice does not have a relevant impact in the total GHG  
389 emission quantification. The conversion from the current conventional management to organic one  
390 will not probably determine a significant improvement. A solution to reduce the global warming  
391 impact resulting from the use of agricultural machinery could be found in reducing soil tillage  
392 practices and using biodiesel fuel (Benedetto 2013).

393 Plants physiological processes, row cropping, and soil contributed to sequester part of the carbon  
394 released during the year. Carbon exchanges measured by Eddy Covariance (NEE) revealed that the  
395 vineyard was able to accumulate, at annual scale, 0.7151 kg CO<sub>2</sub> per kg of grape yield. Further, the  
396 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,  
398 also pointed out that the vineyard was able to offset the CO<sub>2</sub> emissions released during the  
399 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 kg CO<sub>2</sub>-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  
405 (wine making and distribution) in the carbon footprint analysis for determining their potential  
406 environmental implications.

407

408

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419

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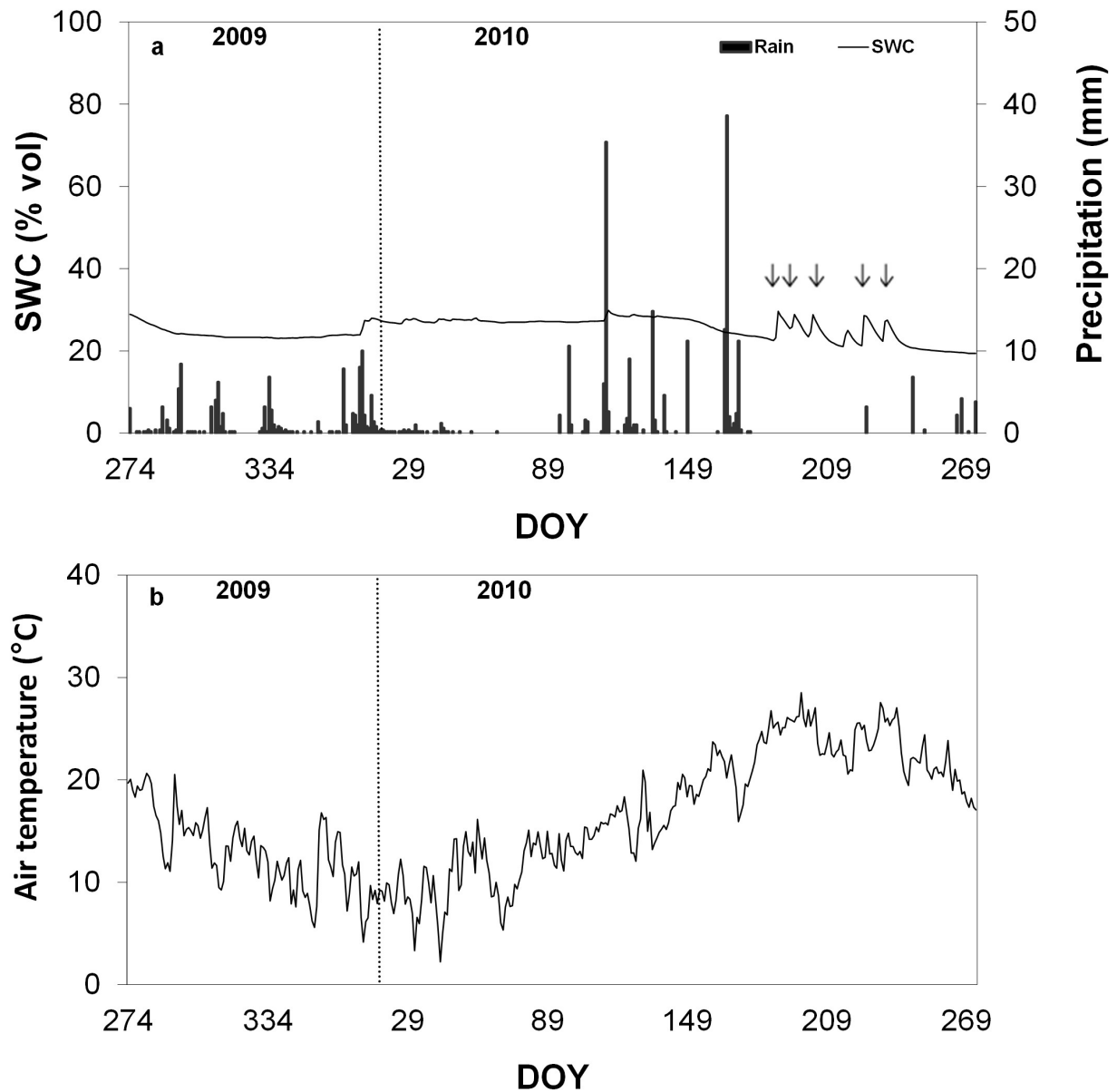
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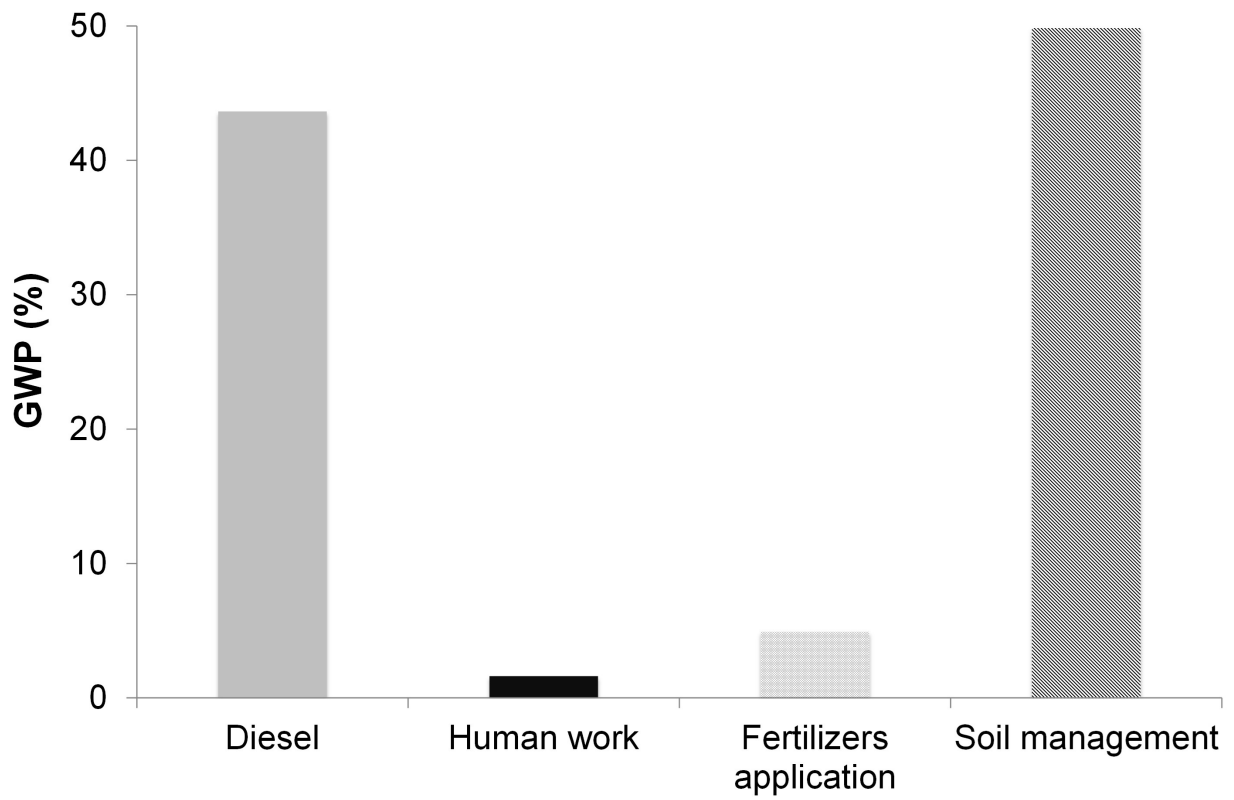
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576 Fig. 1. Variation in daily precipitation (mm), volumetric soil water content (SWC) (average  
 577 between measurements at -0.20 and -0.40 m) (a), and air temperature (°C) (b) in the experimental  
 578 site from October 2009 to September 2010.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

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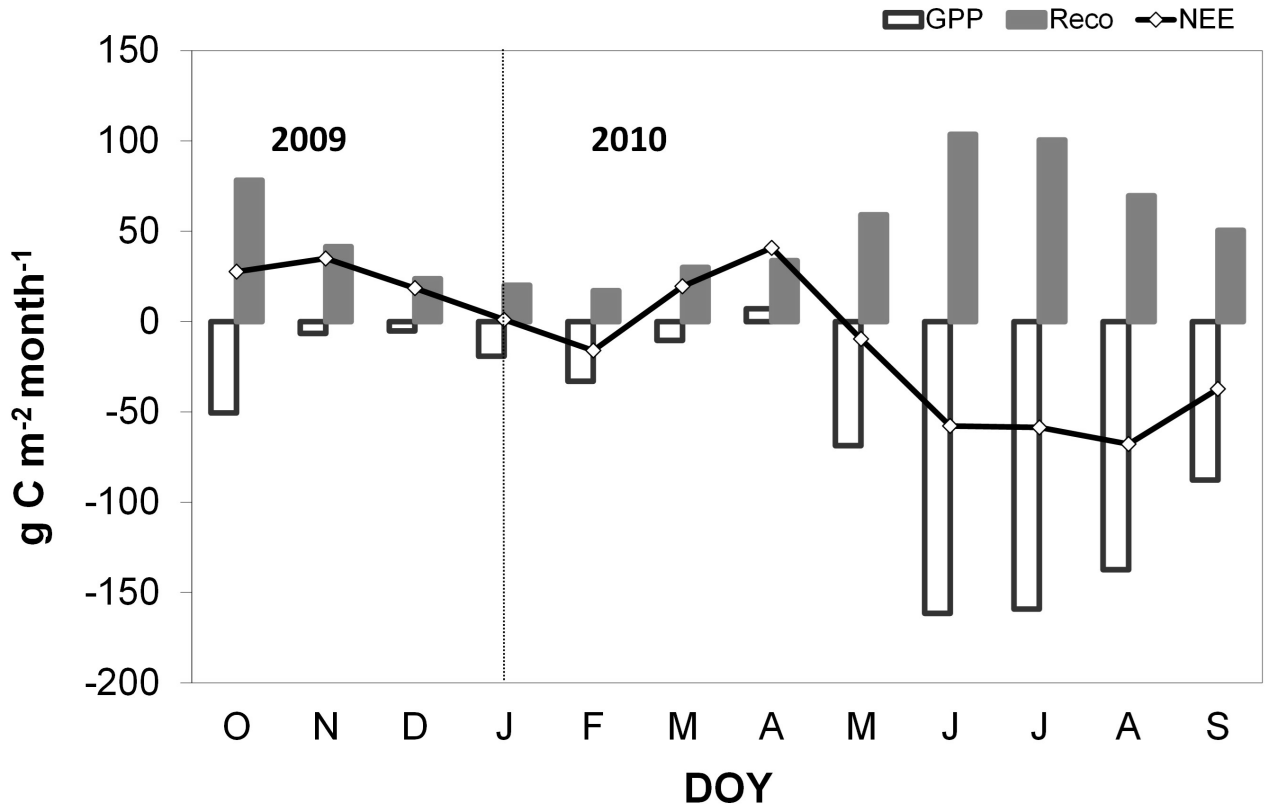


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581 Fig. 2. Global Warming Potential (GWP) impact ( $\text{kg CO}_2\text{-eq kg}^{-1}$  of grape yield, expressed in %  
582 unit) during the grape production phase.

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

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

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	<b>Values</b>	<b>Data source</b>
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

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

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<b>Direct CO<sub>2</sub> emissions</b>		<b>kg kg<sup>-1</sup></b>
A	Fuel consumption for field practices	0.1056
B	Fuel consumption for travels	0.0100
C	Human work	0.0043
D	Crop residues	0.1289
E	Grape yield	0.4783
<b>Indirect CO<sub>2</sub> emissions (from N)</b>		
F	Fertilization application	0.0130
G	Soil management	0.1320
H	Crop residues	0.0009
I	Grapefruit components	0.0070

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

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		<b>NEE</b>	<b>GPP</b>	<b>Reco</b>
		(g C m <sup>-2</sup> month <sup>-1</sup> )		
<b>Year</b>	<b>Month</b>			
<b>2009</b>	October	27.69	-66.58	94.27
	November	40.50	-16.21	56.71
	December	34.15	-15.32	49.48
<b>2010</b>	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

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