

1 **Carbon Footprint assessment on a mature vineyard**

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13 **Highlights:**

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15 Carbon footprint analysis and Eddy Covariance measurements were combined to quantify carbon
16 emissions and uptake in a mature vineyard during the agricultural phase

17 Fossil fuel consumption and soil management are responsible for more than 90 % of total GHG
18 emissions in the field and the production of one kg of grape has a carbon cost of 0.39 kg CO₂-eq.

19 The carbon exchanges measured by Eddy Covariance (NEE) revealed that, at annual scale, the
20 vineyard was a net carbon sink (-195 g C m⁻² yr⁻¹), and it was able to offset GHG emissions
21 deriving from the grape production process.

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25 **Abstract**

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

30 Even if the agricultural phase is recognized by several authors to have a strong environmental
31 impact during the wine production, only a few studies estimate the greenhouse gas (GHG)
32 emissions related to this stage. In addition, the determination of the Carbon Footprint (CF) (i. e.
33 the amount of CO₂ emissions directly and indirectly caused by production process) of the
34 agricultural phase is not a simple task due to the large uncertainty related to local characteristics as
35 well as climate, land, agricultural practices, grape type, and to a general lack of experimental data.

36 The main goal of this work was to determine the CF of the grape production process along one
37 productive year. The CF analysis was conducted in a typical Mediterranean vineyard located in the
38 South of Sardinia (Italy) using 1 kg of grape as functional unit. The system boundary was “from
39 cradle to gate” excluding winemaking processes, distribution, and consumption. In addition, the
40 study was addressed to assess the role of vineyards to act as carbon *sinks* or *sources* at the end of
41 the productive year. The Eddy Covariance technique was used to directly measure the CO₂
42 exchange over the vineyard and the net CO₂ budget was computed by combining the measured
43 fluxes and the GHG emissions estimated by the CF analysis.

44 Results showed that the production of one kg of grape determined a carbon cost of 0.39 kg CO₂-eq
45 and most of the GHG emissions derived from external inputs such as fossil fuel combustion and soil
46 management.

47 In addition, the carbon exchanges measured by Eddy Covariance (NEE) revealed that the vineyard
48 was a net carbon *sink* at annual scale, demonstrating that the vineyard is able to offset the CO₂
49 emissions released during the agronomic practices.

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52 **Keywords:**

53 Carbon balance; Agricultural phase; Grape; Eddy Covariance; GHG emissions; Vineyard
54 management

55

56 **1 Introduction**

57 In recent years, there has been a growing concern related to the eco-sustainability of production
58 processes, and consumers are becoming more interested in environmentally friendly practices,
59 products, and services. The widespread adoption of intensive production systems in agriculture
60 leads to increase soil degradation, loss of biodiversity, reduction in soil organic matter and water,
61 and increase in air and soil pollution (Zabini, 2008). Measures are then needed to promote
62 sustainable production processes. The fourth largest contribution to global emissions is given by
63 agriculture (14%) (Metz et al., 2007), where the wine industry is one of the most important
64 economic sectors in terms of production and distribution worldwide.

65 The International Organisation of Vine and Wine (OIV) states that, in 2012, 252 million hectoliters
66 of wine have been produced on a total vineyard area of about 7.5 million hectares worldwide. The
67 major producing Countries in the Mediterranean Basin (Italy, France, and Spain) reached a total
68 area of approximately 2.6 million hectares and a production of almost 112 million hectoliters (OIV,
69 2013). The noteworthy economic impact of these data makes necessary the development of
70 methodologies aimed to estimate greenhouse gases (GHGs) emitted in the atmosphere from
71 everyday products and services, and to search for useful strategies to reduce them.

72 Life Cycle Thinking (LCT) is a quantitative approach which aims at taking into account all life
73 cycle phases of a product (e.g. extraction of the raw materials, pre-production processes,
74 production, consumption, end-of-life) in a broad range of methodologies and instruments for
75 sustainability assessment and management. Several LCT-based methodologies and instruments for
76 sustainable development have already been developed so far. One of the most known is the Life
77 Cycle Assessment (LCA), a methodology to assess the potential environmental impact of a
78 product/service in terms of individual environmental impact categories (e.g. global warming, human
79 and environmental toxicity, natural resource depletion, ozone layer depletion, summer smog) and
80 along its life cycle phases.

81 The LCA approach represents a useful tool to account for the environmental burdens associated
82 with the different life cycle stages of wine (Petti et al., 2010; Neto et al., 2013; Vázquez-Rowe et
83 al., 2013), providing multiple impact categories to be analyzed. However, LCA also presents
84 disadvantages due to its holistic and comprehensive principles. Consequently, LCT studies
85 developed a number of issue indicators, such as water footprint or carbon footprint (CF) (Čuček et
86 al., 2012; Laurent et al., 2012; Scipioni et al., 2012).

87 CF analysis, as a part of the LCA approach, quantifies CO₂ emissions directly and indirectly caused
88 by an activity or accumulated during the lifecycle of a product or service (Wiedmann and Minks,
89 2007). This approach is able to identify the contribution of a good or service production to climate

90 change considering emissions due to GHGs covered by the Kyoto Protocol (Bosco et al., 2011). It is
91 typically expressed in kg CO₂-equivalent (CO₂-eq), i.e. a measure of the potential greenhouse effect
92 of a gas considering its Global Warming Potential (GWP).

93 Recently, several approaches and guidelines have been developed for accounting GHG emissions,
94 including (1) methodologies at territorial scale developed by the IPCC, (2) the Publicly Available
95 Specification 2050 (PAS 2050) developed by the British Standard Institute and the Carbon Trust
96 (BSI, 2011), and the (3) Greenhouse Gas Protocol (GHG-Protocol) developed by the World
97 Resources Institute and the World Business Council for Sustainable Development (WBCSD/WRI).
98 In the wine sector, the most used protocols are the International Wine Carbon Protocol (IWCP), the
99 French Bilan Carbone (ADEME, 2010), and the OIV-GreenHouse Gas Accounting Protocol (OIV-
100 GHGAP).

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

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

114 In the winemaking process, the agricultural phase has been recognized to contribute from 17%
115 (Rugani et al., 2013) up to 40% (Benedetto, 2013; Neto et al., 2013). Studies reported that the use of
116 pesticides, fertilizers, and diesel consumptions for vineyard practices are the main sources of GHG
117 emissions in the wine chain (Niccolucci et al., 2008; Pizzigallo et al., 2008; Bosco et al., 2011;
118 Point et al., 2012; Benedetto 2013; Rugani et al., 2013; Fusi et al., 2014). However, the
119 determination of the CF in the agricultural phase is not a simple task because of various issues.
120 Large uncertainty in the estimation derives from differences in the local ecosystems, climate
121 conditions, land texture, agricultural practices, and grape varieties (Rugani et al., 2013). In addition,
122 a general lack of experimental data and information makes difficult the CF quantification of this
123 stage.

124 Apart from the production system complexity, a critical point is to include, in the net carbon budget
125 estimation, the carbon sequestered by the different components (soil and grass cover, woody
126 biomass, etc.) of the vineyard system (OIV, 2011). Most of studies assume balance between the
127 biogenic CO₂ sequestered and released back to the atmosphere. As a results, CF analysis usually
128 omits biogenic carbon issues. In addition, studies are largely based on carbon estimates and only
129 part of them is based on experimental data.

130 Micrometeorological methods are commonly applied to directly measure CO₂ exchanges between a
131 system and the lower atmosphere, and the Eddy Covariance (EC) technique is the standard
132 methodology used in the International Monitoring Network Fluxnet (Baldocchi, 2003). EC is a
133 recognized methodology to obtain long-term measurements of CO₂ exchanges between vegetation
134 and the atmosphere and helps in understanding and quantifying ecosystems capacity to absorb
135 atmospheric carbon.

136 Even if the EC method is widely used over different ecosystems around the globe, so far little is
137 known about the vineyard ability to sequester carbon and offset GHG emissions. CO₂ flux
138 measurements over vineyards were usually reported for short measurement periods (a few weeks up
139 to one month in the Mediterranean) (Spano et al., 2004; 2008), apart the three-year period analyzed
140 by Guo et al. (2014) in the arid region of Northwest China.

141 The aim of this work was firstly to determine the CF of the grape production process and, then, to
142 include biogenic carbon fluxes by coupling the CF analysis with direct measurements carried out
143 during the agricultural phase of the production process. The analysis was conducted in a typical
144 Mediterranean vineyard. The IWCP Protocol was used to identify the agronomic practices that
145 mainly contributed to GHG emissions, while an Eddy Covariance tower was set up over the studied
146 vineyard to directly measure the CO₂ flux in the soil-vegetation-atmosphere continuum. This
147 analysis improved our knowledge about the role of a Mediterranean agricultural ecosystem to be
148 carbon *sinks* or *sources* making possible the identification of the main agricultural practices
149 affecting GHG emissions.

150

151 **2 Materials and Methods**

152 *2.1 Carbon Footprint methodology*

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

158 The CF was computed following the International Wine Carbon Protocol (IWCP), and adopting its
159 relative calculator named International Wine Carbon Calculator (IWCC). In this work, only
160 emissions related to Scope 1 or “primary footprint” (i.e. all emissions under the direct control of the
161 farm) were considered and limited to the agricultural phase. Specifically, emissions related to the
162 use of fossil fuels, both for agronomic practices and for travelling from the farm center to the field,
163 and emissions from activities affecting the short-term carbon cycle (e.g. pruning, harvesting, human
164 metabolism of workers).

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

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

172

173 *2.1.1 Calculation methodology*

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

178 CO₂ emissions related to fuel (diesel) consumed for agronomic practices were calculated based on
179 the fuel quantity method of the IWCC by using an emission factor of 74.01 kg CO₂ GJ⁻¹. Fuel
180 consumption due to travels was calculated considering the IWCC travel distance method. Travel
181 distance was 6 km per round-trip for a total of 18 times per year (i.e. 108 km y⁻¹). An emission
182 factor of 2.745 kg CO₂ l⁻¹ diesel (IWCP) was used to estimate CO₂ emissions due to travels.

183 CO₂-eq emissions due to fertilization were calculated considering direct emissions from fertilizers
184 and from managed soil (Calvin et al., 2008). In the experimental site, organic and chemical

185 fertilizers were used with a Nitrogen (N) content of 2% and 9%, respectively. A default value of
186 0.01 was used to estimate N emissions per each fertilizer, while emissions from managed soil were
187 estimated using a factor of 3, following the IWCP. Differences in land cover, soil composition, and
188 climate conditions are not considered in this calculation. Pesticide emissions were not calculated
189 since a few amount (4-7 kg ha⁻¹) of Sulphur compound is applied per year, and it was considered
190 negligible (Fusi et al., 2014).

191 Crop residues after pruning are usually cut and incorporated into the soil. A sample of crop residues
192 was collected and desiccated to estimate an amount of 703.6 kg dry matter ha⁻¹ (Table 1), which
193 was converted in C content (with a default values of 0.5) first and then in CO₂ content, which is
194 considered totally released into the atmosphere during the year. The N content (% N kg⁻¹dry matter)
195 in crop residues was estimated by an emission factor (0.25) derived from literature (Alfano et al.,
196 2011) and then converted in N₂O (kg). CO₂-eq emissions from crop residues were finally calculated
197 using the 310 Global Warming Potential factor (100 years time horizon) (IPCC, 1995).

198 Carbon dioxide emissions related to grape production were calculated in a different way for grape
199 juice and grapefruit components (grape skin, stalks, and grape seeds). Carbon content in the juice
200 (kg C ha⁻¹) was obtained by multiplying the juice amount and the Brix degree (Table 1). A moisture
201 content of 80% on fresh weight (established as mean value from lab analysis) was used to calculate
202 the dry matter content in grape skin, stalks, and grape seeds. Finally, a value of 2.06% (Baraldi et
203 al., 2010) was used to estimate the N content in residues of the grapefruit components (stalks, grape
204 skin, and grape seeds) (700 kg ha⁻¹), which was then converted in CO₂-eq ha⁻¹.

205 The contribution of human labor to climate change is not usually included in LCA and CF analysis,
206 even if this phenomenon is strictly related to anthropogenic activities, especially for viticulture
207 (Rugani et al., 2013). Human labor consumes resources and releases emissions. In line with Rugani
208 et al. (2012), an emission factor of 0.46 kg CO₂ h⁻¹ was used to estimate the total human respiration
209 emissions (http://www.engineeringtoolbox.com/co2-persons-d_691.html).

210

211 *2.2 Micrometeorological measurements*

212 The Eddy Covariance (EC) technique, a non-intrusive micrometeorological methodology
213 commonly used in the international monitoring networks, was used to directly measure the
214 exchanges of energy and mass (carbon and water) between the vineyard and the atmosphere. The
215 EC system was set up in June 2009 at 2.8 m above the ground. The EC system consisted of an
216 IRGA Li-7500 open-path gas infrared analyzer (Li-Cor Biosciences, Lincoln, NE, USA), a CSAT3
217 three-dimensional sonic anemometer (Campbell Scientific Inc. (CSI), Logan, UT, USA), and a

218 CR5000 datalogger (CSI). Solar panels supplied energy to the tower. Eddy Covariance data were
219 acquired at 10 Hz and averaged every 30 minutes.

220 Raw data were processed using the EddyPro v. 4.2.1 software developed by Li-Cor Biosciences.
221 The amount of data removed by quality check was 18% over the entire study period (October 2009-
222 September 2010).

223 Net ecosystem exchange (NEE) is the net CO₂ exchange with the atmosphere directly measured
224 with the EC technique. Positive NEE values represent net C emissions to the atmosphere and
225 negative values are the C uptake from the atmosphere, according to the atmospheric science
226 convention.

227 Ecosystem respiration (Reco) and gross primary productivity (GPP) were estimated with the
228 marginal distribution sampling method (MDS) (Reichstein et al., 2005), implemented in
229 <http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/> (2013 version). The online tool was also used to
230 fill gaps in the dataset.

231 Four heat flux plates (mod. HFP01SC, Hukseflux, Delft, NL) were located, along a transect
232 between rows, at -0.07 m soil depth to have a representative measure of soil heat flux (G). Soil
233 temperature changes in the soil layer above -0.07 m were measured to correct G for heat storage.

234 The energy balance closure was used to evaluate the accuracy of measured data. In the literature,
235 deviations of about 20-30% from closure are commonly observed in surface energy budget
236 measurements (Twine et al., 2000; Wilson et al., 2002). The observed energy balance closure was in
237 line with those reported in the literature (slope = 0.76; R² = 0.86), so the measurements accuracy
238 was considered acceptable.

239 Meteorological and radiometric stations were also placed in the site to measure the main
240 meteorological variables and the radiation balance components, respectively. Air temperature (T_{air},
241 °C), relative humidity (RH, %), precipitation (P_{cp}, mm), photosynthetically active radiation (PAR,
242 μmol quanta m⁻² s⁻¹), and incoming and outgoing solar radiation (W m⁻²) were measured. During
243 the growing period, the Leaf Area Index (LAI) was also monitored by LAI-2000 (Li-cor, Lincoln,
244 NE, USA) based on the principle of interception of the light radiation from vegetation. In addition,
245 soil temperature and moisture were monitored at -0.20, -0.40, and -0.60 m depths in several
246 vineyard locations.

247

248 *2.3 Experimental site*

249 The study was conducted in a typical Mediterranean vineyard located in the South of Sardinia, Italy
250 (39°21'43" N, 9°07'26" E, 112 m asl). The 8-hectare vineyard was planted in 2000. The grapevine
251 variety is Vermentino, which is trained in a Guyot system. The rows are oriented in east-west

252 direction with 0.8 m between plants and 2.1 m between rows (5952 vines ha⁻¹). Vegetation is about
253 2.0 m tall with 50% ground shading of the clay soil. The vineyard is irrigated during the dry season
254 through a drip system. Leaf Area Index (LAI) in the period May-September varies from 1.2 to 3.2.

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256

257

258 **3 Results and Discussion**

259

260 *3.1 Environmental conditions in the experimental site*

261 Climate is typical of the Mediterranean area, with a mean annual temperature of 16.9 °C and a mean
262 annual precipitation of 484 mm. Annual precipitation measured at the site, in the period 1st October
263 2009-30th September 2010, was 518 mm, mainly concentrated in spring and fall (Fig. 1a). Soil
264 volumetric water content (SWC) ranged from 0.19% to 0.30% during the year, with an average soil
265 moisture value of about 0.25% (Fig. 1a). Mean annual temperature was 15.5 °C, slightly lower than
266 climate mean. Daily mean temperature ranged from 1.6 °C to 28.2 °C (Fig. 1b), with a minimum in
267 February 2010 (-1.9 °C) and a maximum in August 2010 (37.6 °C).

268

269 *3.2 Carbon footprint analysis*

270 Direct and indirect CO₂ (i.e. N₂O emissions converted into CO₂-eq) emissions per each practice
271 were quantified and results are reported in Table 2. Results are expressed per hectare and then
272 reported per kg of grape yield.

273 Human induced emissions related to the agronomic practices (fuel consumption, human work,
274 fertilization application, and soil management) conducted during the examined period totaled 2648
275 kg CO₂-eq ha⁻¹ y⁻¹ (0.26 kg CO₂-eq kg⁻¹). The main processes affecting the GWP impact in the
276 grape production phase were represented by diesel consumption (sum of emissions due to the use of
277 fuel both for field practices and travels from the farm center to the field) and N₂O released by the
278 managed soil. These two inputs are responsible for more than 90% of the total GHG emissions (Fig.
279 2). On average, diesel consumption covered 44% of the GWP impact, while emissions from
280 managed soil accounted for 50%. Similar results were found by other authors (Benedetto 2013; Fusi
281 et al., 2014; Neto et al., 2013; Point et al., 2012; Venkat, 2012). A contribution of 20% for diesel
282 and around 20-30% for N₂O emissions from soil management after fertilization was observed by
283 Bosco et al. (2011) in different vineyards in Tuscany (Italy). The impact of fertilization application
284 is around 5%, which is similar to the values reported in Spain (7%) by Vázquez-Rowe et al. (2012a)
285 but lower than what reported by Bosco et al. (2011) and Point et al. (2012). However, differences in
286 local climate conditions, grape variety, soil characteristics, and agricultural practices could explain
287 the variability observed in the results from different studies (Rugani et al., 2013). Most of the
288 analysis in the literature agreed that the amount of consumed diesel and fertilization application
289 should be revised to guarantee a net improvement in environmental impacts (Neto et al., 2013;
290 Vázquez-Rowe et al., 2012b).

291 In this study, results of the CF analysis showed a total amount of GHG emissions (fuel
292 consumption, human respiration, fertilization, and emissions from soil and crop residues) of 3946
293 kg CO₂-eq ha⁻¹ y⁻¹. Since a grape yield of 10000 kg is obtained during the year, the production of
294 one kg of grape had a final cost of about 0.39 kg CO₂-eq kg⁻¹.

295 Our results are in line with other studies that analyzed emissions during the grape production phase.
296 In general, CO₂-eq emissions ranging from 0.20 to 0.67 kg⁻¹ grape yield were found by Venkat
297 (2012) and Vázquez-Rowe et al., (2012b). Other studies refer the CF results to the 0.75 l wine bottle
298 as functional unit, which corresponds to 1.1 kg of grape product, so it makes difficult the
299 comparison with our results. However, they found values around 0.30 (Bosco et al., 2011), 0.50
300 (Gazulla et al., 2010) and 0.80 kg CO₂-eq (Point et al., 2012) during the agricultural phase. It should
301 be also noted that in each study, differences in vineyard management and grape yield, CF
302 methodologies and external inputs considered concur to determine the differences in the final
303 results, but all contribute to understanding the role played by vineyards in the GHG emissions.

304

305 3.3 Micrometeorological measurements

306 This work represents one of the few studies reporting carbon fluxes measured over a vineyard
307 during a long measurement period (one year). The average Net Ecosystem Exchange (NEE)
308 measured by the Eddy Covariance at the experimental site was -0.53 g C m⁻² day⁻¹. The maximum
309 daily carbon uptake occurred on 25 July 2010 (-5.58 g C m⁻² day⁻¹), while the maximum C net loss
310 was registered on 22 April 2010 (5.07 g C m⁻² day⁻¹). Data related to the carbon budget at monthly
311 scale are presented in Fig. 3.

312 Results reveal that the vineyard was a net carbon *sink* during the growing period (May-September),
313 when green vegetation is present. Most of the carbon uptake was recorded in July and August (-100
314 g C m⁻² and -108 g C m⁻², respectively). During the growing period, Reco ranged from 76 g C m⁻²
315 (September) to 134 g C m⁻² (June) (Table 3).

316 Positive NEE values (net C emissions) occurred in winter and early spring up to 46 g C m⁻² in April
317 2010. Row cropping between rows clearly decreased the release of carbon when plant leaves were
318 missing. Lower values of carbon emissions are, in fact, observed in January 2010 and October 2009
319 (Table 3). In addition, soil tillage practices have a direct effect on increasing soil carbon emissions.
320 The decrease in C release from November 2009 to February 2010 is clearly interrupted by the use
321 of tractors to till the soil, resulting in carbon peaks emissions in March and April 2010 (Fig. 3,
322 Table 3).

323 At annual scale, the vineyard was a net C *sink* with an uptake of 195 g C m⁻² yr⁻¹. This amount is
324 lower than carbon sequestered by other vineyard ecosystems, e.g. 868 g C m⁻² y⁻¹, as reported by

325 Guo et al. (2014) during a three_year measurement period, or forest sites (Valentini et al., 1996),
326 and agricultural ecosystems (Hollinger et al., 2005; Schmidt et al., 2012), while it is similar
327 (Matthias et al., 2012; Mudge et al., 2011) or higher (Zenone et al., 2013) to grassland ecosystems,
328 showing that vineyard could have a strong carbon sink efficiency. In terms of CO₂, our vineyard
329 was able to annually sequester 715.05 g CO₂ m⁻².

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

337

338 *3.4 Combined analysis for net carbon budget calculation*

339 As observed by other authors (Soosay et al., 2012), agricultural phase may contribute up to 28% of
340 the emissions due to decomposing biomass, timber decay and sequestration linked to vine growth
341 and sugar production in the grapes. Since the difficulty to have reliable measurements or estimates
342 of these quantities (Bosco et al., 2011), most of the studies assumed that the amount of biogenic
343 CO₂ sequestered from the atmosphere during vine and grape growth is equal to the amount of CO₂
344 released back to the atmosphere by the oxidation of carbon in pruning wastes and grapes (Neto et
345 al., 2013) or they did not account for short-term processes (Pattara et al., 2012). As a results, CF
346 analysis usually omits biogenic carbon issues, even if they have been taken up by CF guidelines
347 (i.e. PAS 2050).

348 Our study tried to include biogenic carbon sequestration and release into the CF calculation. These
349 processes are the result of both the grape physiological activity (ecosystems photosynthesis and
350 respiration) and the external inputs (fuel consumption, fertilization, soil emissions, and human
351 work).

352 The Net Ecosystem Exchange (NEE) measured by the Eddy Covariance tower represents the net
353 carbon sequestered by the vineyard (-7151 kg CO₂ ha⁻¹ y⁻¹). It derives from sequestration and
354 decomposition of plant components after pruning (i.e. D, Table 2) and emissions due to fuel
355 combustion for field practices (A) and human work (C) (Table 2). Emissions from fuel combustion
356 and human work are external inputs that the EC tower only accounts as C removal from the system.
357 These terms are then added to NEE to adjust it and obtain the total C sequestered by the vineyard (-
358 8250 kg CO₂ ha⁻¹ y⁻¹). In addition, biogenic carbon sequestered by grape yield (E) needs to be

359 removed from NEE to quantify the net biomass accumulation along the production year. The net
360 biomass sequestration (Biom) of the mature vineyard was calculated as:

361

$$362 \quad \text{Biom} = \text{NEE} + \text{A} + \text{C} - \text{E} \quad (\text{kg CO}_2 \text{ ha}^{-1} \text{ y}^{-1}) \quad (1)$$

363

364 and results showed an annual increase sequestration equal to 3466 kg CO₂ ha⁻¹ y⁻¹. Since annual
365 grape production per hectare is 10000 kg, the production of one kg of grape causes a sequestration
366 of about 0.35 kg CO₂-eq. In terms of biomass, this amount corresponds to about 945 kg C ha⁻¹ y⁻¹ or
367 1718 kg d.m. ha⁻¹ y⁻¹ (i.e. 0.29 kg d.m. plant⁻¹ y⁻¹).

368 When the external energy inputs (fuel for travels, B, and fertilizers, F, Table 2) and CO₂-eq
369 emissions from managed soil, crop residues, and grape fruit components (G, H, I, Table 2) are
370 considered, the final carbon cost (CC) of the grape production process was calculated as:

371

$$372 \quad \text{CC} = -\text{NEE} + \text{E} + \text{B} + \text{F} + \text{G} + \text{H} + \text{I} \quad \text{kg CO}_2\text{-eq ha}^{-1} \text{ y}^{-1} \quad (2)$$

373

374 Results from eq. 2 show that, considering the current vineyard management, the net carbon budget
375 is positive with a net gain of -748 kg CO₂-eq ha⁻¹ y⁻¹, which corresponds to 0.07 kg CO₂-eq
376 sequestered per kg of product.

377 Fuel consumption in the field (A) is one of the most terms affecting results, and we first assumed
378 that this emission amount was totally (100%) registered by the EC tower. Our results, then, show
379 that the vineyard was able to offset GHG emissions related to the grape production processes.
380 However, measurements of the turbulent flux (NEE) are strictly linked to the wind direction, wind
381 intensity, and other conditions that may occur when tractors are working in the field. Since it is hard
382 to relate the EC footprint with the tractor positions during the measurement period, other two
383 hypotheses were made accounting for the 50% and 30% of fuel consumption emissions included
384 into the NEE adjusted values. In the first case, the vineyard was still able to offset GHG emissions
385 by sequestering 0.02 kg CO₂-eq kg⁻¹, while in the second hypothesis the balance was negative with
386 total emissions of 0.004 kg CO₂-eq kg⁻¹.

387

388 **4 Conclusions**

389 This work presents results of the application of two coupled methodologies to quantify the global
390 warming impact of the grape production process during a productive year. Carbon Footprint
391 analysis was conducted in a vineyard located in the South of Sardinia (Italy) and coupled with direct
392 measurements of CO₂ fluxes through the Eddy Covariance technique, with the aim to quantify the

393 GHG emissions during a productive year and to evaluate the role of a Mediterranean vineyard to be
394 carbon *sinks* or *sources* in the global carbon budget.

395 Results showed that, in the experimental site, the production of one kg of grape has a carbon cost of
396 0.39 kg CO₂-eq. The main terms responsible for CO₂ emissions in the atmosphere are the fossil fuel
397 combustion and soil emissions. These results are in accordance with findings in the literature. Since
398 farmer already reduced the amount of fertilizers applied, this practice does not have a relevant
399 impact in the total GHG emission quantification. The conversion from the current conventional
400 management to organic one will not probably determine significant improvement. A solution to
401 reduce the global warming impact resulting from the use of agricultural machinery during the
402 mechanical operations conducted in the vineyard could be found reducing soil tillage practices and
403 using biodiesel fuel (Benedetto 2013).

404 In addition, the carbon exchanges measured by Eddy Covariance (NEE) revealed that the vineyard
405 was a net carbon *sink* at annual scale (-7151 kg CO₂ ha⁻¹ y⁻¹). Plants physiological processes, row
406 cropping, and soil contributed to sequester part of this quantity. The net carbon balance calculated
407 by coupling the CF results with the measured carbon exchanges, revealed that the vineyard was able
408 to totally or partially offset the CO₂ emissions released during the agronomic practices, depending
409 on the fuel emissions amount assumed to be registered by the EC tower (100%, 50%, or 30%).
410 Further, the plants were able to growth of about 1718 kg d.m. ha⁻¹ y⁻¹.

411 This study represents an advancement in knowledge since a few studies focused only on the
412 agricultural phase of the wine making process and it represents the first attempt to relate GHG
413 emissions of the grape production process to the effective capacity of the vineyard system to offset
414 them in the field. Further steps of this research study will consist in including the other stages of the
415 production process (wine making and distribution) in the carbon footprint analysis for determining
416 their potential environmental implications.

417

418

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424 tecnologico nella filiera del vino di qualità” within the Accordo di Programma Quadro in materia di
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429

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

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

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

Direct CO₂ emissions		kg kg⁻¹
A	Fuel consumption for field practices	0.1056
B	Fuel consumption for travels	0.0100
C	Human work	0.0043
D	Crop residues	0.1289
E	Grape yield	0.4783
Indirect CO₂ emissions (from N)		
F	Fertilization application	0.0130
G	Soil management	0.1320
H	Crop residues	0.0009
I	Grapefruit components	0.0070

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

		NEE	GPP	Reco
		(g C 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

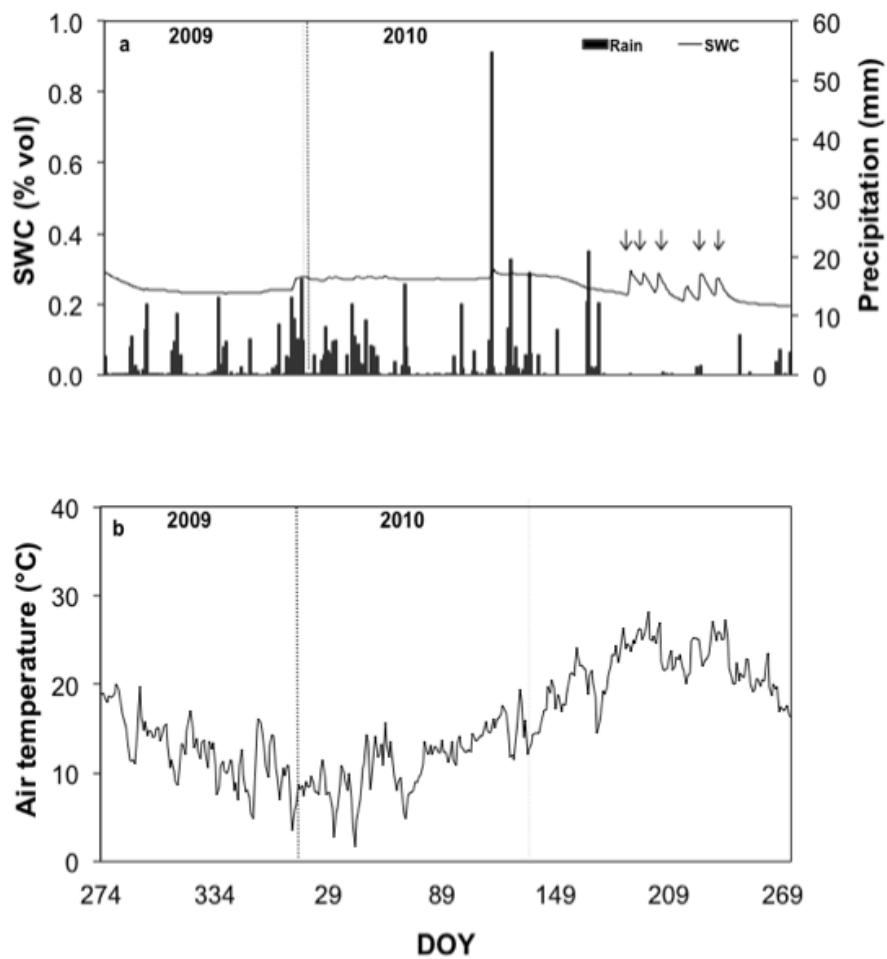


Fig. 1. Variation in daily precipitation (mm), soil volumetric water content (SWC) at -0.025 m (a), and air temperature (°C) (b) in the experimental site from October 2009 to September 2010. Arrows in the upper plot indicate irrigation.

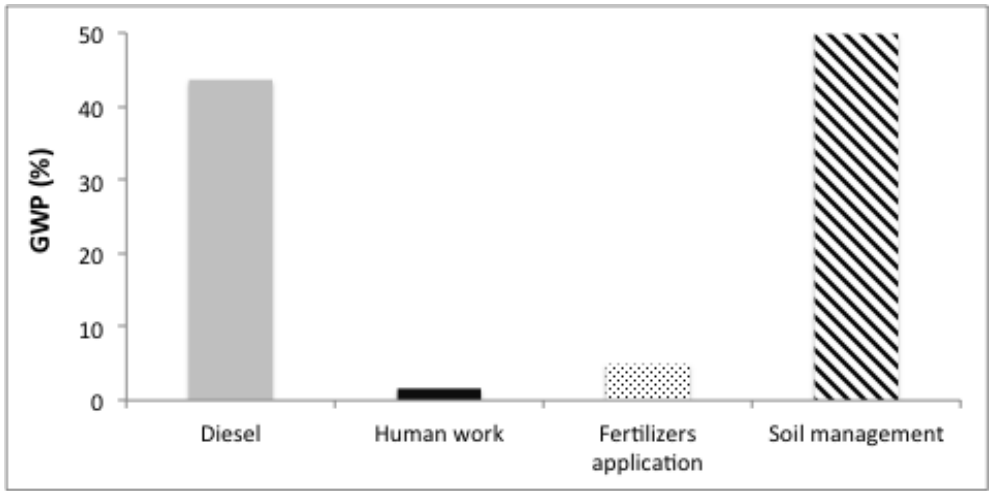


Fig. 2. Global Warming Potential (GWP) impact ($\text{kg CO}_2\text{-eq kg}^{-1}$ of grape yield) during the grape production phase.

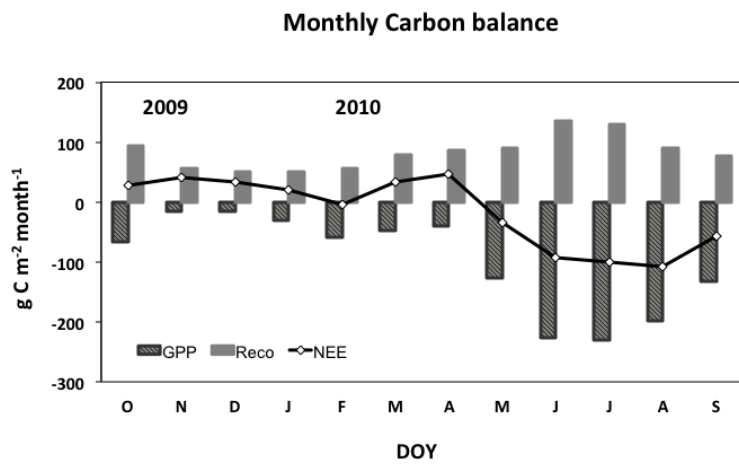


Fig. 3. Monthly variation in measured net carbon fluxes ($\text{g C m}^{-2} \text{ month}^{-1}$).