

- 1) Brunori, E., Farina, R., Biasi, R.

[Sustainable viticulture: The carbon-sink function of the vineyard agro-ecosystem](#)

(2016) Agriculture, Ecosystems and Environment, 223, pp. 10-21. Cited 51 times.

- 1) <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84959344791&doi=10.1016%2fj.agee.2016.02.012&partnerID=40&md5=>
DOI: 10.1016/j.agee.2016.02.012

Document Type: Article

Publication Stage: Final

Source: Scopus

1 **Type of paper:** Original Article

2

3 **Sustainable viticulture: the carbon-sink function of the vineyard agro-ecosystem.**

4 **Elena BRUNORI¹, Roberta FARINA², Rita BIASI^{1*}.**

5 ¹ *Department of Innovation in Biological, Agro-food and Forest Systems (DIBAF) University of*
6 *Tuscia– Viterbo (Italy)*

7 ² *Consiglio per la Ricerca in agricoltura e l'analisi dell'Economia Agraria (CREA) - Centro di*
8 *ricerca per lo studio delle relazioni tra pianta e suolo (RPS) - Roma (Italy)*

9 **Corresponding author : Biasi,+39761357537, Email: biasi@unitus.it*

10

11 ***ABSTRACT***

12 In addition to food production, tree crop-based agrosystems can provide other ecosystem services
13 (ES) such as soil fertility maintenance, soil and water retention and landscape preservation. Tree
14 crops can also act as carbon (C) storage facilities and climate change mitigating systems. We focus
15 on the nature of viticulture as a provider of ES, in particular C storage. This study has been carried
16 out focusing on two different wine-grape growing areas in central Italy (Latium region; natural and
17 peri-urban hilly areas) where the vines (*Vitis vinifera* sativa L., cv Merlot) were cultivated according
18 to two different management techniques (conventional vs organic farming). Grapevine C storage
19 levels were analyzed in the two main vine C pools during the 2011 and 2012 growing seasons, i.e.
20 above-ground and below-ground biomass, in accordance with the Net Ecosystem Production (NEP)
21 methodology. In order to quantify C sequestration at the vineyard level, we determined soil C
22 sequestration and soil functionality through the measurement of Total Organic Carbon (TOC),
23 microbial biomass and soil and grapevine root respiration. To conclude, the net C balance was
24 assessed at both the grapevine and the vineyard scale.

25 Although the highest dry matter partitioning in the grapevines was measured in the above-ground
26 organs, the root systems contributed to between 9 and 26% of the total vine C fixation. The soil's C

fixation was maximized in the organically managed vineyards (73,35 tC ha⁻¹). The CO₂ eq sequestration of one hectare of vineyard ranged between 5,72 (±0,07) to 7,23(±1,11) tC ha⁻¹·year⁻¹. Soil respiration represented the main (99%) CO₂ emission source in the vineyard agro-ecosystems. The Principal Component Analysis (PCA) indicated that the soil physical characteristics, the grapevine's biological properties, and the vineyard's management techniques, like those handling the inter-row space that highly differ in the organic and conventional farming, turned out to be the main factors influencing the soil's C storage and consequently the vineyard's C balance. Together, these findings prove that vineyards can act as C sinks, if properly managed. Furthermore, vineyards could represent a crucial cropping system able to provide pivotal ecological services such as carbon dioxide sequestration. Viticulture can also contribute to the preservation and regulation of natural resources -such as soil and agricultural landscapes-, according to the new European Commune Agricultural Policy (CAP).

Key words: *atmosphere quality, grapevine carbon partitioning, organic farming, multifunctional agriculture, soil functionality.*

Highlights

- The carbon sink function of the vineyard agro-ecosystem was measured.
- C fixation was assessed in relation to environmental and agronomical management.
- The root system's contribution to total C storage ranged from 9% to 26%.
- The highest level of soil organic C was found in the organic vineyard.
- Total C storage in the vineyard ranged from 5.7 to 7.2 tC ha⁻¹year⁻¹.

1. INTRODUCTION

Grapevine (*Vitis vinifera* sativa L.) cultivation still represent one of the most widespread agricultural production systems in many European countries (OIV, 2013) despite the observed downward trend following the implementation of the European CAP's (Common Agricultural Policy) measures against overproduction. On the other hand, many other countries e.g, China and the New World Mediterranean (California, Chile, South Africa, Australia) (Viers at al., 2013), are expanding their vineyard surfaces for wine production. Vineyards are therefore characterizing traits of agricultural landscapes in territories with extremely different environments. This is a consequence of the grapevine's high plasticity and genotypes that easily adapt to a variety of climates and soils. In Italy, the wine-grape growing areas cover different percentages of the landscape's eco-mosaic depending on the interaction with other land uses or land covers. In central Italy, viticulture can be wide - scattered /fragmented in highly natural territories, as well as in intensively cultivated areas and even in peri-urban spaces (Biasi and Brunori, 2012). In each context, sustainability is a goal to be met by viticulture in the future [COM (2011) 130 final/2]. This can be achieved through the protection of environmental resources like biodiversity and landscape (Biasi et al., 2011), through the adaptation and/or counteraction of climate changes and through the provision of high quality grape and oenological production while assuring economic profitability. Among the benefits of sustainable agriculture, there is the provision of ecosystem services (ES), defined in the Millennium Ecosystem Assessment (MEA, 2005) as 'the benefits people obtain from ecosystems', both natural and managed'. These can be categorized as provisional (feed, food, timber, biofuel), regulating (C sequestration, pests, diseases), cultural, and supporting services (soil formation, nutrient cycling) (MEA, 2005).

Soil organic matter (SOM) is a key attribute that influences the soil's ability to support ecosystem services (Stockmann et al., 2013). SOM assures important functions concerning habitat, biological diversity, soil fertility, crop production potential, erosion control, water retention, chemical elements

78 exchange between soil, atmosphere and water, and the filtering, buffering and nutrient cycling
79 capacity (Stockmann et al., 2013).

80 Different land uses and soil management techniques can damage soil quality and functions, reducing
81 the quantity and quality of the ecosystem services. Thus, the cropping systems' C sequestration
82 potential is a crucial ecosystem service that has acquired importance due to its potential to
83 counterbalance the global increase in atmospheric greenhouse gases (GHG), including CO₂ (Lal,
84 2011). This is particularly important in peri-urban and urban spaces. Nowadays, carbon dioxide
85 depletion through photosynthesis and soil C sequestration has mainly been attributed to forest areas
86 and natural land covers. Perennial agricultural crops store C in their woody biomass (Kroodsma and
87 Field, 2006) and in their extensive deep root systems (e.g., Agnelli et al., 2014; Smart et al., 2007).
88 However, less consideration has been given to these crops in relation to the influence they exert on
89 soil C sequestration. Attributing the carbon sink function to fruit and vine orchards is a rather new
90 concept (Holmes et al., 2015; Sofo et al., 2005). So far numerous studies have addressed C balance
91 assessments in fruit trees and vines. These have mainly been conducted to quantify C allocation
92 among plant organs to ensure the optimization of agronomical techniques and product quality. The
93 evaluation of the vineyards' potential to store C acquires great importance in the agro-environmental
94 schemes of the Common Agricultural Policy (CAP) and in the framework of the UE decision
95 529/2013 concerning C accounting for the Kyoto protocol.

96 For these reasons, the objective of this research is to quantify the C storage potential of vineyards by
97 calculating the amount of net C fixation in above and below ground grapevine organs, eliminating the
98 losses for root respiration, and taking into account the contribution of the soil systems under different
99 environmental conditions (climate and soil characteristics) and under two cropping scenarios
100 (conventional vs organic farming). Among the different models for the estimation of C balance, we
101 selected the Net ecosystem production –NEP balance because it considered the root system's
102 contribution to the C balance (Lovett et al., 2006). NEP was initially defined by Whittaker and
103 Woodwell (1968) as the difference between the ecosystem's photosynthetic gain of CO₂-C (gross

primary production, or GPP) and the ecosystem's (plant, animal, and microbial) respiratory loss of CO₂-C (ecosystem respiration, or ER). The knowledge of all factors contributing to the C balance, including roots, is of utmost importance in the selection of the best management techniques to maximise C storage and CO₂ sequestration in the vineyards while minimising losses. The research's tested hypotheses were: i) that the grapevine (*Vitis vinifera* sativa L.) and the vineyard are strong carbon sinks and therefore they can act as efficient C storage systems, and ii) that the choice between the two main vineyard management models (in this case conventional vs organic farming) can affect C storage efficiency in the agro-ecosystems.

2. MATERIAL AND METHODS

2.1 Plant material and vineyard description

The study has been carried out on vines of *Vitis vinifera* sativa L., cv Merlot, one of the most widespread international grapevine genotypes. The vines were ten-years old and grafted on *berlandieri* x *rupestris*. All the vineyard agro-ecosystem's C storage measurements have been carried out in two different kinds of traditional wine-grape growing areas in central Italy: i) a highly natural territory of the Latium region (PDO - Colli Etruschi Viterbesi, northern of Rome), in two vineyards under organic and conventional management (43° 30' 57,11" N - 12° 14' 33,76" E and 42° 33' 30,93" N - 12° 14' 40,20" E, respectively), where viticulture represents less than 15% of the agricultural utilized areas (AUA) and ii) a peri-urban territory (PDO - Castelli Romani, southern of Rome) where vineyards represent up to 40% of the agricultural utilized area (AUA) (ISTAT, 2011) in a conventionally managed vineyard (41°47'05,26"N – 12°38'51,03"E) (Figure 1). Both environments were located in hilly territories at an average altitude of 204 and 183 meters a.s.l., respectively. In both environments, the vineyard's architecture was based on vertical shoot trellis systems, i.e. cordon, with an average planting density of 5600 vines per hectare (0.80 x 2.30 m between the vines and between the rows, respectively). Each vine had one 80 cm-long cordon, horizontally posed and an average bud charge of 8-10 buds per vine. The vineyard's conventional management technique was standard (use of chemical fertilizers and agrochemicals). On the other

Carbon storage capacity in the grape vine was calculated following the Net Ecosystem Production (NEP) methodology (Lovett et al., 2006). NEP evaluates the C storage potential of a biological system by determining the amount of dry matter produced seasonally in the two main C pools, i.e. above-ground and below-ground biomass. In each model vineyard, the above-ground biomass was calculated in the 2011 and 2012 seasons, in six vines, randomly distributed in the vineyard, by measuring the dry-weight (DW) (obtained at 65 °C in a forced-air oven to constant weight according to Keller and Koblet (1995) of leaves, lateral shoots, primary shoots and bunches at their final stage of development. In order to assess the root system's seasonal dry matter production, fine root samples were taken in conformity with the dual-peck model of root regeneration in *Vitis vinifera* (Mullins, 1992) three times during the growing season, i.e. before bud burst (time 0), at anthesis and end of wood maturation. Root biomass was quantified through the ingrowth-cores method based on replacing the intact core removed from the ground with an equivalent volume of root-free soil (Flower-Ellis and Persson, 1980; Vogt et al., 1998). At time 0 the ingrowth-cores were installed in the field. For each vine replication one core was made (diameter = 0.07 m) at 0.50 m of distance from the trunk along the vineyard row; the distance was selected to exceed the canopy's thickness. The area around the ingrowth-cores was kept free of grasses in order to avoid any root contamination from non-grapevine sources. Given that the majority of grapevine roots are found in the top 0.60 m of the soil (Mullins, 1992), soil samples were taken at three different depths for each core replication, i.e. at 0-0.20, 0.20-0.40 and 0.40-0.60 m depth. All fine roots were removed by sieving the soil through a 2 mm diameter mesh and DW was measured. Total root biomass was calculated considering root renewal in a volume of 0.6m³/vine (depth 0.60 m; width canopy 1.0 m; length 1.0 m) (Figure 2).

2.4 Vineyard CO₂ seasonal fixation

The equivalents of total carbon dioxide (CO₂) fixed seasonally were calculated according to the following formula (3) (modified from Landsberg, 1980):

184

185 tons of CO₂ eq. • ha⁻¹ • year⁻¹ = (3.666/2 • 10⁶) • N° Grapevines • $\left[\sum_{i=0}^3 (DW_{Ri}) + (DW_{Bui} + DW_{Li} + DW_{Wi} + DW_{LSi})\right]$ (3)

186 where:

187 DW_{Ri}: dry weight of roots in *i* active growth and reserve accumulation phase

188 DW_{Bui}: dry weight of the bunches at maturity

189 DW_{Li}: dry weight of the leaves at maturity

190 DW_{Wi}: dry weight of pruned mature wood

191 DW_{LSi}: dry weight of later shoots removed at fruit set

192 N° Grapevine: Number of plants/ ha

193 0-3: the four phenological phases in which it was divided by the annual cycle of the *Vitis vinifera*: 0–reserve

194 carbohydrates remobilization; 1- shoot and leaf growth; 2–Fruit growth and ripening; 3- dormancy.

195 10⁶: conversion factor for hectare (ha)

196 ½Conversion factor: 50% of the dry weight is the C fixed (IPCC, 2003)

197 3.666: conversion factor from C to CO₂ equivalent (Coto-Millan et al., 2008).

198

199 **2.5 Soil carbon sequestration and soil functionality**

200 In autumn the bulk soil samples were collected in the vineyards far from soil tillage. Three samples
201 were taken from each vineyard at three different depths: (0-0.20) m, (0.20-0.40)m and (0.40-0.60)m
202 using a 0.03 m diameter soil corer. We determined the soil's water content and we used it to correct
203 the segment's weight in order to calculate the soil's bulk density. The other part of the soil's core was
204 air dried until it crumbled effortlessly. After that, all easily identified plant materials such as roots,
205 stems, leaves, and plant crowns were removed. The remaining soil samples were sieved at 2.0 mm
206 and dried at 38°C until constant weight was reached. Three subsamples for each of the cleaned and
207 sieved samples were used for the total carbon content (TOC) determination. The soil's TOC was
208 determined in the dried sediments using a LECO CR-412 Carbon Analyzer (LECO Corp., St. Joseph,
209 MI, USA).

210 The microbial biomass carbon (MBC) was measured in the (0-0.20) m depth soil samples using the
211 fumigation-extraction with chloroform method (Vance et al., 1987). Moist samples (three replicates)

212 were incubated in desiccators for 24 hours at room temperature in the presence and absence of
213 chloroform vapour. Soluble C was extracted with 0.5M K₂SO₄ and determined by digestion with
214 K₂Cr₂O₇ and titration with FeSO₄.

215 **2.5.1 Soil functionality**

216 The sieved and dried soil samples were then used to determine other soil quality indexes such as: i)
217 physical indicators i.e. soil texture (Andrews et al., 2002), ii) soil pH, measured in deionized water
218 with a glass electrode and iii) organic nitrogen reserves (total N), measured using Kjeldahl's
219 procedure.

220 Soil microbial activity was assessed using the metabolic quotient (the specific soil respiration of the
221 microbial biomass, qCO₂), the C mineralization quotient (the fraction of total organic C mineralized
222 throughout the incubation, qM) and the microbial biomass C / total organic C (MBC/TOC) ratio
223 (Moscatelli et al., 2005).

224 **2.6 Grapevine and Vineyard Carbon Balance**

225 The net C balance was assessed at both the grapevine and vineyard levels, through the subtraction of
226 inputs (C stored in the above and below-ground grapevine organs) from the outputs. The outputs
227 considered were the grapevine root respiration, for the vine level C balance computation, and soil
228 respiration for the C balance computation at the vineyard's (whole agro-ecosystem) level.

229 The grapevine root's respiration rate, was measured using the BaPS-Barometric Process Separation
230 (UMS GmbH Gmunder Str. 37 D-81379 München) (Ingwersen et al., 1999), a barometric chamber
231 working in isothermal and gas tight conditions. In the barometric chamber, pressure changes indicate
232 the dominant process occurring (respiration, nitrification, denitrification). Furthermore, the software
233 allowed for the calculation of each process rate.

234 From three-year-old potted vines cv Merlot/*berlandieri* x *rupestris* grown in the same soil of each
235 model vineyard, six replicated soil cores (2 cores x 3 vines) were taken with circular stainless cores
236 (0.07 m diameter), and then incubated inside the BaPS at 25 °C for 12 h. After this, using the same
237 samples, all visible grapevine roots were removed, weighted and, after adjusting for humidity, they

were inserted in the BAPS machine once again. The difference of the soil respiration levels in the two scenarios “with roots” and “after roots removal”, has been considered as a measure of root respiration in a known amount of soil. The total amount of CO₂ detected was divided by the roots’ dry weight and expressed in g of CO₂ per g of roots. The pots’ system, did not include any vegetation other than the grapevine itself as the soil was constantly kept clean from grasses. Therefore, in this experiment any contribution of roots from non-grapevine sources is not included. This value has been related to each grapevine’s root zone (0.6 m³), below-ground biomass (root respiration at grapevine level) and per planting density (root respiration at vineyard level). As far as soil respiration goes, soil samples (three replicas for each depth of the core) at water holding capacity were incubated at 30°C, in darkness and in an airtight jar with a beaker containing sodium hydroxide (NaOH) 0.5N. At days 1,2,4,7,10,14,17,21 and 28 after the incubation, BaCl₂ was added to NaOH in order to precipitate the CO₂ as BaCO₃. CO₂ produced by soil respiration was finally quantified by titration of BaCO₃ solution with HCl (Anderson, 1982).

2.7 Statistical analysis

The statistical analysis (inferential, multivariate and factorial analysis in particular Principal Component Analysis - PCA) was performed using the R package (R Development Core Team, 2005, <http://www.R-project.org>). PCA is used to reduce the dimension of large multivariate datasets. The statistical analysis led to the identification of a number of derived variables such as , the principal components (axes), which are linear combinations of the original variables. In the interpretation of the PCA results, the amount of information provided by the principals axes is given by the corresponding eigenvalues, along with their percentages to the total inertia and the cumulate percentage. Then, for every variable it is possible to refer to: i) its correlation (Pearson’s coefficient) with the axes, a measure of the quality of representation of the variables on the axes, and ii) the cumulate quality, that is the multiple correlation of the variables with the first principal axes up to the considered one, a measure of the share of the variable’s variance explained by the set of axes taken into account.

264 The experimental design consists of two environmental conditions (natural and peri-urban area) in
265 which data were collected in conventionally managed vineyards in two seasons (2011 and 2012). For
266 the first type of environment, i.e. the natural area, a comparison between vineyards under different
267 management techniques (conventional vs organic farming) was made. Data were collected from six
268 vines in each vineyard. Three replicates randomly distributed on each vine were sampled in an
269 attempt to detect biomass allocation (dry weight) in the grapevine's organs.

270 The two-way analysis of variance (ANOVA) was carried out. One analysis with environmental
271 condition (E) and season (S) as the main factors, and a second one with vineyard's management (M)
272 and seasons (S) as key factors. The significance of mean differences (at a value of $p < 0.05$ and
273 $p < 0.01$) was then tested.

274 **3. RESULTS**

275 **3.1 Climate characterization**

276 The climate index mean values, which have been recorded in the two studied areas in the period
277 2004 to 2012, are shown in table 2. In these decades, we observed both increasing linear trends of IH,
278 IW, CI and extreme events (number of day with $T_{max} > 30^{\circ}C$). Following the multi criteria
279 climatic classification system (Tonietto and Carbonneau, 2004), the peri-urban and natural areas were
280 characterized by warm conditions during the grapevine's growing cycle, and by temperate nights
281 during the grape's maturation period. These indexes are useful to analyze the intra-annual climate
282 variability. In fact, the metropolitan area of Rome showed highly statistically significant differences
283 between the 2011 and 2012 indexes. Despite being statistically significant, though, these values were
284 not as different from the mean of the last decades in the area considered. On the contrary, in the
285 natural area north of Rome, the 2011 and 2012 climate indexes differed from the past average trend,
286 being much higher than the measurements of the last 10 years. Both years, in fact, were characterized
287 by warmer growing seasons, and 2011 registered the lowest rainfall compared to the last decade's
288 average (Figure S1 a and b - supplementary material).

289 **3.2 Grapevine carbon storage**

290 The total grapevine C storage (Table 3) was calculated from the annual above-ground and below-
291 ground vine dry biomasses. The C storage represents the input of C fixation in the vineyard's agro-
292 ecosystem necessary to determine the vineyard's net C balance which equals the difference between
293 the uptake and release of CO₂ from roots and soil respiration. C storage among grapevine organs
294 differs between seasons and is affected by both environmental and management systems (organic vs
295 conventional farming) as specified below.

296 ***3.2.1 Natural grape growing area***

297 In the natural grape growing area the average vine dry biomass under the organic regime was 2025.4
298 (± 520.3) g dry biomass·vine⁻¹·year⁻¹ and 2060.5 (± 275.9) g dry biomass·vine⁻¹·year⁻¹, for the 2011
299 and 2012 seasons, respectively. On the other hand, under conventional farming the total biomass
300 level reached 1890.0 (± 388.9) g dry biomass·vine⁻¹·year⁻¹ in 2011, and 2592.9 (± 397.1) g dry
301 biomass·vine⁻¹·year⁻¹ in the 2012.

302 In this environment, the organic vineyard stored on average 5.35 (± 0.07) tC ha⁻¹·year⁻¹, while the
303 conventional one 6.28 (± 1.39) tC·ha⁻¹·year⁻¹ (Table 3). The annual above-ground biomass accounted
304 for 90.4% and 88% of the total biomass C in the organic and conventional vineyards, respectively.

305 The vineyard's management regime influenced the grapevine's organ contribution to C fixation to a
306 greater extent (Table 4). In particular, conventionally grown vines show a greater difference in C
307 allocation between organs due to annual climate variability, when compared to organically grown
308 vines (Table 4). The average value of below-ground biomass in the period 2011-2012, represents
309 10% and 12 % of the total vine C biomass in organic and conventional vineyards, respectively.

310

311

312 ***3.2.2 Peri-urban grape growing area***

313 In the peri-urban area vines produced 2359.1 (± 440.3) g dry biomass vine⁻¹·year⁻¹ and 2862.7
314 (± 354.2) g dry biomass vine⁻¹·year⁻¹, for the 2011 and 2012 season, respectively.

315 On average the conventionally managed peri-urban vineyard was able to fix $7.31 (\pm 1.11) \text{ tC ha}^{-1}$
316 year^{-1} . The most significant portion of storage contribution was due to bunches, but root turn-over
317 also contributed to 25.7% of the total C biomass in the 2011 season (Table 4). Finally C allocation in
318 the vines' organs proved to be significantly different in each season, as in the environment
319 considered above.

320 **3.3 Soil carbon sequestration and functionality indexes**

321 The organic and conventional vineyards in the natural grape growing areas were characterized by
322 respectively a clay-loam and clay texture, based on the ISSS's classification (Table 5). The soil's
323 nitrogen and C contents were consistently higher in the organic vineyard than in the conventional one
324 at all depths. In fact, TOC in the organic vineyard's soil amounted to $73.35 (\pm 16.61) \text{ tC} \cdot \text{ha}^{-1}$ in the
325 upper 0.20 m depth and $168.44 (\pm 15.52) \text{ tC} \cdot \text{ha}^{-1}$ between 0 and 0.60 m depth, i.e. when the whole
326 soil explored by roots was considered. The conventional vineyard soil's C pool amounted to $44.16 (\pm$
327 $8.23) \text{ tC} \cdot \text{ha}^{-1}$ and $117.25 (\pm 5.82) \text{ tC} \cdot \text{ha}^{-1}$ at 0.20 m and 0.60 m of depth, respectively. These were the
328 lowest values for all depths.

329 Similarly, the MBC (microbial biomass carbon) and the microbial activity (basal respiration - Rb)
330 values were higher in the organic vineyard than in the conventional one. In particular, the soil basal
331 respiration for the organic vineyard was $17.44 \text{ mg C-CO}_2 \cdot \text{kg dry soil}^{-1}$; this value is about two-times
332 higher than the one observed in the conventional agro-ecosystem ($7.69 \text{ mg C-CO}_2 \cdot \text{kg dry soil}^{-1}$)
333 (Table 5). Furthermore, other indicators of microbial activity (like $q\text{CO}_2$, $q\text{M}$) were higher in the
334 organic than in the conventional vineyard as well.

335 In the peri-urban grape growing area the vineyard was characterized by a sandy-loam texture
336 (according to ISSS classification). High amounts of TOC, probably derived from the previous years'
337 organic management (organic farming ended in the 2010 season – vineyard in conversion), were
338 measured; in fact TOC amounted to $68.74 (\pm 13.66) \text{ tC} \cdot \text{ha}^{-1}$ in the first 0.20 m depth and, when
339 considering the whole depth (0-0.60m) reached the cumulative value of $127.05 (\pm 22.87) \text{ tC} \cdot \text{ha}^{-1}$.

340 The MBC and microbial activity (Rb) values were the highest recorded for vineyards, while other

indexes were intermediate compared to other vineyards' values (i.e., organic and conventional vineyards in the natural area) (Table 5).

3.4 From Grapevine to Vineyard carbon balance

The grapevine's C balance was assessed net of root respiration. On the other hand, the vineyard's C balance was assessed net of soil respiration. At the grapevine level, the root respiration rate, calculated per root unit weight, amounted to $696.52 \mu\text{g C-CO}_2 \cdot \text{kg dry soil}^{-1} \cdot \text{h}^{-1}$. This value was then used to calculate the roots' respiration per vines at the vineyard's level. This parameter was correlated to: planting density (5600 vine/hectare), below-ground biomass per vine, and root soil volume (0.6 m^3) per vine. This data has been used as an output for the vineyard's C balance (see paragraph 4.4).

Figure 3 shows the differences in the grapevine's and vineyard's C balance in the two environments considered (natural vs peri-urban area) (Figure 3 a-d and Figure 3 e-f, respectively) and under two different management systems (organic vs conventional farming) (Figure 3 a-b and Figure 3 c-f, in comparison).

At the grapevine level (Figure 3 a, c and e), all cases studied (i.e. two environments and two management systems, conventional and organic) show a negative C storage (CO_2 fixed in the biological system), while at the vineyard level (Figure 3 b, d and f), only one agro-ecosystem shows a negative C storage, i.e. the conventional vineyard in the natural area.

According to vineyard C storage, in this natural area the organic vineyard captured $6.22 (\pm 0.6) \text{ t eq.CO}_2 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$. On the other hand, the conventional vineyard, both in the same environmental area and in the peri-urban one, emitted $15.4 (\pm 1.1)$ and $17.41 (\pm 2.82) \text{ t eq.CO}_2 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$.

3.5 Multivariate statistical analysis

PCA analysis has been employed in order to identify which factors i.e. the management model, season and the environment influenced the grapevine and vineyard's carbon sink potential the most.

367 This analysis determined which parameters enhanced the grapevine's carbon sink function in the
368 same environment, based on the vineyard's managements model (conventional and organic farming)
369 or season.

370 In addition, PCA led to the identification of the factors that better explain the diversity in soil
371 functionality and in the carbon sink function of the vineyard. This allowed to highlight the
372 differences between the tested environments.

373 **3.5.1 Carbon balance: Principal component analysis (PCA)**

374 The Principal component analysis (PCA) was based on a sample comprising the analytical results
375 from the NEP assessment of the six vines for each vineyard agro-ecosystems, in two growing
376 seasons, 2011 and 2012. We selected two principal axes of interest that explained about 61% of the
377 total variation (measured by the inertia) (correlation table not shown). 60% is the minimum cumulate
378 quality of representation of all parameters, this means that the result constitutes a sufficient level for
379 our exploratory purposes (Camiz et al., 2008).

380 In our case (Figure S2 – supplementary material) the first axis of the PCA graphs corresponds to the
381 seasonal gradient (2011-2012), while the second axis concurs with a gradient of vineyard
382 management regime (organic and conventional). All six vines (Figure S2 – supplementary material)
383 were separated according to the season and the management regime. This proved that climate and
384 agronomic management can strongly influence the grapevine's C storage ability.

385 **3.5.2 Soil characters: Principal component analysis (PCA)**

386 The principal component analysis (PCA) was also carried out for the soil's functional indicators in
387 order to assess the relationship between the physical, chemical and microbiological soil traits and the
388 vineyards' management systems (correlation table not shown). Two principal axes were selected and
389 these explained 67.4% (I PC) and 32.6% (II PC) data variability (Figure 4). The first PC was related
390 to physical and microbiological parameters (content of clay, silt and sand, basal and cumulative
391 respiration (Rb and Rcum) and microbial biomass (MBC), whereas the second PC was correlated to
392 chemical parameters like pH, total nitrogen (N) and C content (TOC). The conventional vineyard in

the natural area proved to be affected by qCO_2 (Figure 4), while the organic one was affected by TOC and N, and their ratio; the vineyard in the peri-urban area was linked to soil physical parameters and qM (Figure 4).

Moreover, in order to assess the soil's organic C content evolution we analyzed the correlation between qCO_2 and TOC (Figure 5a) and qM and TOC (Figure 5b).

The qCO_2 functional indicators showed an exponential trend related to TOC ($R^2 = 0.5265$) while qM showed a polynomial trend ($R^2 = 0.4661$). Also, in this case, a gradient related to the vineyard's management was identified: from conventional, to conversion (agro-ecosystem in the peri-urban area) to organic regime.

3.5.3 The effects of environmental, seasonal and vineyards management techniques on grapevine biomass production.

When jointly considered, the grapevine's behaviors in terms of biomass production showed to be related to the growing environment, as well as to the season (i.e. climate) and management technique. The biomass produced by leaves, lateral shoots and annual wood showed significant differences in the environmental (E) and seasonal (S) factors, while biomass of bunches and roots was not affected by these factors (supplementary data). The season also significantly affected the total biomass production (Table S1- supplementary data). The interaction (ExS) had an effect on lateral shoots, annual wood, bunches and total biomass production per vine.

Factorial analysis was carried out for the seasonal (S) and vineyard's management system (M) (conventional vs organic) factors and their interaction (SxM) (Table S2 - supplementary data). The seasonal factor affected the biomass production (DW) of leaves, lateral shoots, bunches. In contrast the vineyard's management technique and the SxM interaction showed significant differences only for lateral shoots' development.

4. DISCUSSION

4.1 Grapevine carbon sink function

419 The results underline how viticulture can act as a cropping system significantly contributing to C
420 sequestration and CO₂ emissions control. The first hypothesis to be verified in this study was the
421 capability of grapevines to efficiently stock C throughout the growing season.

422 In all three cases studied, grapevines proved to be able to store significant quantities of C both in
423 above-ground and below-ground biomasses. On average, the biomass values calculated for the cv
424 Merlot grapevines were greater in the peri-urban area that is characterized by a higher human
425 pressure (Salvati, 2013), than the natural area. Our results, when considering exclusively above-
426 ground biomass, match the literature's ones (Castelan-Estrada et al., 2002; Poni et al., 2006), which
427 also analyses the cv Merlot and other grapevine varieties in the Mediterranean environment.

428 It is interesting that the value of C storage found at grapevine and vineyard level in our peri-urban
429 grape growing area was the highest measured among all the tested conditions. Some authors
430 measured through field experiments an increase in grapevine biomass production under increasing
431 CO₂ exposure levels (Bindi et al., 2001). On the other hand Gratani and Varone (2014) measured an
432 increase in CO₂ concentration in the peri-urban area of Rome. This suggests a possible link among
433 grapevine's biomass production, increasing environmental CO₂ and peri-urban contexts, to be
434 investigated in further researches.

435 In order to optimize the grapevines' C sink functions it may be useful to analyse the differences
436 observed in the C storage's contributions of each grapevine organ. In particular, canopy management
437 techniques like summer pruning, can significantly influence C allocation by altering the hormonal
438 balance and affecting the physiological functions (Mullins, 1992). Summer pruning, in fact, modifies
439 light penetration, leaf structure, photosynthesis activity and carbohydrate reserve allocation (Mullins,
440 1992). In a summer pruning scenario, our findings highlight a decrease, of bunch and roots and an
441 increase of the leaves' contribution to total grapevine biomass, without any negative repercussion on
442 grape quality, such as sugar concentration and phenolic component (data not shown). Overall results
443 show that canopy summer pruning might be a valuable tool to improve the vineyard's carbon sink
444 function. Further research for the evaluation of the effect of specific agronomical practices in the

vineyard on C allocation may be needed to better understand the influence of vineyard management techniques on C storage.

The results underline the significant contribution of below-ground biomass to C storage. This ranges from 9 % to 26% in the natural and peri-urban areas, respectively. In particular, the highest value (25.7% - in the 2011 season) was measured in the peri-urban area vineyard. Furthermore, the increased root turnover might be due to the very sandy soil texture (60% of sand), and consequently low soil water content and other abiotic factors such as the relatively higher mean air temperature in peri-urban areas, as found by other authors (Morlat and Jacquet, 1993). On the other hand, in the natural area, the lower root system's C storage could be due to the pedological feature (clay content ranging between 40 and 42%, in our experimental conditions) and the lower mean air temperature (to which lower soil temperature could be related), which jointly contribute to the reduction of the grapevine's root growth (Comas et al., 2010; Morlat and Jacquet, 1993). Our data highlight the role of roots as C storage pools. The root's contribution to C storage is an innovative notion. This is due to the current limited understanding of the roots' dynamics and their interaction with pedo-climatic factors, especially under field conditions in forestry and agricultural systems. The root's contribution to C storage is often overestimated when using the root to shoot ratio (Comas et al., 2010; Keightley, 2011; Mullins et al., 1992) or not taken into consideration for tree C storage computation (Castelan-Estrada et al., 2002; Poni et al., 2006). The amount of total C stored in the below-ground biomass reported in the bibliography (from 1,75 to 6,5 tC·ha⁻¹·year⁻¹) (Agnelli et al., 2014; Carlisle et al., 2010; Castelan-Estrada et al., 2002; Poni et al., 2006), is consistent with the C storage we measured in all three case studies. Taken together these experimental evidences prove the grapevine's efficiency in storing C under different environmental and technical conditions.

4.2 Soil carbon sink function

The hypothesis that vineyard management can affect C storage in soil was verified discussing the results in terms of how microbial activity and soil respiration, that are both highly influenced by the

470 farming systems, may affect TOC quantity and composition, as well as CO₂ losses owing to soil
 471 respiration.

472 The TOC of the vineyard soils in the environments studied are two times greater than those reported
 473 in the literature (Agnelli et al., 2014; Chiti et al., 2012; Holmes et al., 2015). These are comparable to
 474 those found in forest systems in William et al. (2011) in Mediterranean-type ecosystems (North
 475 California). These authors examined the partitioning of above-ground and soil C stocks in vineyards
 476 and adjoining wildlands on ranches in different landscapes. Wildland habitats ranged from riparian
 477 vegetation to oak woodlands, to closed-canopy mixed conifer-hardwood forest 15-25 m in height,
 478 interspersed with patches of grassland. Wildlands habitats proved to store on average 36.8 Mg C/ha
 479 in aboveground woody biomass and 89.3 Mg C/ha in soil. In our case in particular, the TOC of
 480 organic and conventional vineyards in natural grape growing areas, amounts to 73.35 and 44.16
 481 tC·ha⁻¹ in the first 0,20 m depth, respectively. These values are compatible with those found in
 482 different forest soils (measured values 32-55 tC·ha⁻¹) (Agnelli et al., 2014; Chiti et al., 2012; Holmes
 483 et al., 2015). This result emphasizes the role of the vineyard's soil in maintaining the soil's C pool
 484 and in preserving environmental quality, mitigating climate change, and opposing to increasing tCO₂
 485 in air levels, as observed for many other agricultural soils (Eve et al., 2001; Smart et al., 2007).

486 The soil's organic matter characterization shows that 1% of the TOC is represented by microbial
 487 biomass (MBC) in conventional vineyards, whereas in the organic microbial biomass the amount is
 488 halved (0.5%). The MBC values for the agro-ecosystems in the natural grape growing area are closer
 489 to 140 µgC·g dry soil⁻¹; these value of MBC is similar to that found by Gonzalez-Quñones et al.
 490 (2011) that is indicated as constraining for soil quality.

491 In other words, although the biomass's absolute values are comparable to those reported in the
 492 literature for vineyard systems (de Oliveira Freitas et al., 2011), our studies show that MBC does not
 493 make a positive contribution to TOC (0.5%), in particular in the organic vineyard. Furthermore, an
 494 altered microbiological soil balance seems to be present.

495 A higher microbial activity (microbiological indicators) is indeed observed in the organic agro-
496 ecosystem rather than in the conventional one. This might be caused by the higher amounts of labile
497 substrate introduced in the vineyard by the organic amendment. In fact, following the organic
498 farming protocols amendments, including manure, are largely used as the soil's microbiota favourite
499 C source (de Oliveira Freitas et al., 2011). Furthermore, organic farming relies on mechanical
500 weeding (harrowing) compared to conventional farming that uses herbicides. As a matter of fact,
501 herbicides are able to kill a large portion of the soil's microbial population before their degradation
502 takes place (Domsch et al., 1983). These repeated soil disturbances in our studied organic system,
503 did not caused an high organic matter mineralisation (contrary of what demonstrated by Domsch et
504 al., 1983), but in the future may undermine the organic systems' ability to retain carbon and nitrogen.
505 Our statistical analysis proves that the most important contribution to microbial activity is connected
506 to qCO_2 , and that its exponential trend is related to TOC, higher in organically managed agro-
507 ecosystems. The increase of qCO_2 could be interpreted as an indicator of stress and disturbance, as
508 proved by other authors (Gonzalez-Quñones et al., 2011). In organic vineyards, the higher qCO_2
509 levels could reflect stress conditions for the microbial biomass (Moscatelli et al., 2005).

510 All soil respiration rates in the three agro-ecosystem assessed in this study can be compared to those
511 obtained by the Eddy Covariance technique applied to citrus groves, or through the IRGA analyser
512 on orange groves (Liguori et al., 2009), on vineyard soils (Carlisle et al., 2006; de Oliveira Freitas et
513 al., 2011; Huang et al., 2005). However, in general, the vineyard's soil respiration remains lower
514 than the soil's respiration rate calculated in forest systems (Carlisle et al., 2006; Smart et al., 2007).

515 Soil respiration (heterotrophic respiration) represents the main CO_2 emission source in the vineyard's
516 agro-ecosystem. This is controlled by physical-chemical factors such as TOC, fine roots' density and
517 microbial biomass, but also by abiotic factors like soil temperature and moisture (Comas et al., 2010;
518 Freibauer, 2004). In particular in the peri-urban vineyard, the soil respiration level reached the
519 highest value. This may be caused by its significant soil porosity (sandy soil,) which promotes
520 microbial biomass and root turn-over (Carlisle et al., 2010). Moreover the PCA analysis applied to

soil functional indexes shows how the conventionally managed vineyard of the peri-urban area (still in this type of soil) is highly correlated to the mineralization quotient (qM), that here reaches its highest value.

Soil respiration can be also related to the vineyard's soil management in all three vineyards studied. In particular, in the natural area, the comparison between soil respiration rates for the organic and the conventional regimes show higher values in the organic vineyard than in the conventional one. This is also confirmed by the existing literature (de Oliveira Freitas et al., 2011; Liguori et al., 2009; Williams and Hedlund, 2013).

The inter-row space represents a large fraction of the vineyard agro-ecosystem. Therefore vineyard soil management techniques may strongly influence the vineyards' ability to sequester the soil's C. Tillage, including light tillage such as surface disking, disturbs the soil, breaking up aggregates and exposing previously protected soil organic matter to microbial decomposition resulting in oxidation and loss of soil C (Carlisle et al., 2010).

No-tilled inter-rows, on the other hand, enhance soil C sequestration and decrease the soil's respiration rate, as measured for the vineyards under conventional management in the natural grape growing area. Here, the no-tillage soil management helps to reduce the heterotrophic respiration (lowest value) and enhances the ability to sequester C into the soil. Our result is consistent with other studies (Carlisle et al., 2010). In general, this confirms that cropping systems, like grapevine cultivation, may provide greater potential for C sequestration because their soil is less disturbed. This can be achieved through the frequent adoption of floor covering that is not adopted in annual crop systems (Steewerth et al., 2010). It must be mentioned that perennial crops, like tree and vines crops, have been recently indicated by the FAO as strategic agro-ecosystems for agricultural sustainability (<http://www.fao.org/fileadmin/templates/agphome/documents/scpi/PerennialPolicyBrief.pdf>).

4.3 Vineyards carbon balance

Despite the intrinsic potential of grapevine to sequester C, our results indicate that vineyard inter-row management techniques (i.e. tillage vs no tillage floor management) can affect the carbon sink

547 function of the whole agro-ecosystem (Carlisle, et al., 2010; Steenwerth, et al., 2010), jeopardizing
548 the vineyard's ability to mitigate climate change. This is a relevant issue to be addressed for
549 sustainable agriculture. In particular, the only agro-ecosystem able to sequester CO₂, turns out to be
550 the conventionally managed vineyard in the natural area. This is an interesting result as the most
551 relevant grapevine carbon sink function was found in the vineyard of the peri-urban area and not in
552 the natural area.

553 Certainly soil respiration is the most important factor in determining the agro-ecosystem's C balance
554 (Stockmann et al., 2013) which is the ratio between emissions and sequestration of CO₂,
555 Consequently, any factor affecting soil respiration can originate a positive C balance which means
556 that the vineyard emits more CO₂ than it is able to fix.

557 **5. CONCLUSION**

558 Jointly considered, the results suggest the presence of a carbon sink function exerted by viticulture,
559 one of the most representative perennial cropping systems in the Mediterranean basin. This
560 underlines the role that permanent cropping systems may play in mitigating greenhouses gas
561 emissions (CO₂). This function may be crucial especially in areas characterized by high human
562 pressures, like peri-urban agricultural spaces, where the maintenance of grapevine ecosystem services
563 may represent an attempt to improve environmental quality and therefore viticultural sustainability.

564 Our results suggest that vineyard management practices, in particular, the vineyard's soil
565 management, may affect the vine's carbon sink function. Organic farming is generally thought to
566 preserve the soil's ecosystem services, and therefore is usually considered a more sustainable
567 method for food production compared to conventional farming. However, evidence for this is
568 equivocal, and little is known about the potential trade-offs between soil functions, which can be
569 classified as supporting and provisioning ecosystem services, in conventional and organic systems.
570 In particular in the peri-urban area, where soil consumption and soil degradation risks are higher due
571 to urban sprawl, it is important to provide multiple ecosystem services, as viticulture does, in order to

enhance the sustainability of agricultural land uses and safeguard the quality of the environmental natural resources.

Finally, understanding the crucial role of viticulture in providing ecosystem services could allow the objective of resilient agricultural landscapes, against soil consumption and land degradation that represent the challenge of the new CAP, as well as of the ONU 2030 Agenda, and imply the adoption of measures for sustaining their maintenance, being traditional viticultural landscapes still present in many European peri-urban contests .

SUPPLEMENTARY DATA

Supplementary files contain the thermopluviometric diagram in two grape-wine growing zones of the Latium region (Figure S1a and S1b), the PCA of Net Ecosystem Production (NEP) assessment in vines of the natural grape growing area (Figure S2), and the significance of the two-way analysis of variance (ANOVA) (Table S1 and Table S2).

ACKNOWLEDGEMENTS –PhD research co-funded by the University Consortium of Velletri (CUV), Italy. The author thank the viticultural farms Castel De Paolis - Grottaferrata (Rome), and the Cooperative Farm ColleValle AgriNatura– Bomarzo (Viterbo) for kindly hosting the trials; Dr. Barbara FELICI and Dr. Melania MIGLIORE of CREA-RPS (Rome) for assistance in soil analysis.

REFERENCES

- Agnelli, A., Bol, R., Trumbore, S. E., Dixon, L., Cocco, S., and Corti, G., 2014. Carbon and nitrogen in soil and vine roots in harrowed and grass-covered vineyards. *Agric. Ecosyst. Environ.* 193, 70-82.
- Anderson, J.P.E., 1982. Soil respiration. in: Page, A.L. (eds), *Methods of soil analysis, Part.2 Chemical and Microbial Properties*. Vol. 9, 2nd edn ASA-SSSA. Madison, WI, pp. 831-871.
- Andrews, S.S., Karlen, D.L., Mitchell, J.P., 2002. A comparison of soil quality indexing methods for vegetable production systems in Northern California. *Agric. Ecosyst. Environ.* 90, 25–45.

596 Biasi, R., Barbera, G., Marino, E., Brunori, E., Nieddu, G., 2011. Viticulture as crucial cropping
 597 system for counteracting the desertification of coastal land. *Acta Hort.* 931, 71-77.

598 Biasi, R., Brunori, E., 2012. Urban viticulture: the case study of the peri-urban area of Rome. in:
 599 Mauget, J.C., Godet, S., Nguyen A., (Eds), *Book of Abstract - Symposium on Horticulture in*
 600 *Europe*. Angers, 2012, pp. 346. Printed by Hexa Repro, 85 rue Ferdinand Vest – 49800 Trélazé.
 601 June 2012.

602 Bindi, M., Fibbi, L., Miglietta, F., 2001. Free Air CO₂ Enrichment (FACE) of grapevine (*Vitis*
 603 *Vinifera* L.): II. Growth and quality of grape and wine in response to elevated CO₂
 604 concentrations. *Eu. J. Agron.* 14, 145–155.

605 Camiz, S., Altieri, A., Manes, F., 2008. Pollution Bioindicators: Statistical Analysis of a Case Study.
 606 *Water Air Soil Poll.* 194, 111–139.

607 Carlisle, E.A., Steenwerth, K.L., Smart, D.R., 2006. Effects of land use on soil respiration:
 608 conversion of oak woodlands to vineyards. *J. Environ. Qual.* 35, 1396-1404.

609 Carlisle, E., Smart, D., Williams, L.E., Summer, M., 2010. California Vineyard Greenhouse Gas
 610 Emissions: Assessment of the Available Literature and Determination of Research Needs. Final
 611 Report September 2010 – California sustainable winegrowing alliance.
 612 www.sustainablewinegrowing.org

613 Castelan-Estarda, M., Vivin, P., Gaudillere, J.P., 2002. Allometric relationships to estimate seasonal
 614 above-ground vegetative and reproductive biomass of *Vitis Vinifera* L. *Ann. Bot.* 89, 401-408.

615 Chiti, T., Gardin, L., Perugini, L., Quarantino, R., Vaccari, F.P., Miglietta, F., and Valentini, R., 2012.
 616 Soil organic carbon stock assessment for the different cropland land uses in Italy. *Biol. Fert. soils*,
 617 48 (1), 9-17.

618 Comas, L.H., Bauerle, T.L., Eissenstat, D.M., 2010. Biological and environmental factors
 619 controlling root dynamics and function: effects of root ageing and soil moisture. *Aust. J. Grape*
 620 *Wine Res.* 16, 131-137.

621 Coto-Millan, P., Domenech Quesada, J. L., Mateo Mantecon, I., 2008. Corporate Ecological
622 Footprint: New Conversion Factors . Research Lett. Ecol. , Article ID 415934, 4 pp.

623 de Oliveira Freitas, N., Mayumi Yano-Melo, A., Barbosa da Silva, F.S., de Melo, N.F., Costa Maia,
624 L., 2011. Soil biochemistry and microbial activity in vineyards under conventional and organic
625 management at Northeast Brazil . Sci. Agric., 68 (2), 223-229.

626 Domsch, K. H., Jagnow, G., Anderson, T. H. 1983. An ecological concept for the assessment of side-
627 effects of agrochemicals on soil microorganisms. in: *Residue Reviews*. Springer New York, 1983.
628 pp. 65-105.

629 Eve, M.D., Paustian K., Follet, R.F., Elliot, E.T., 2001. An inventory of carbon emissions and
630 sequestration in United States cropland soils. In Soil Carbon Sequestration and the Greenhouse
631 Effect, ed. R. Lal. Madison, WI: Soil Science Society of America. ISBN-10: 0891188509

632 Flower-Ellis, J.G.K., Persson, H., 1980. Investigations of structural properties and dynamics of Scots
633 pine stands. Structure and Function of Northern Coniferous Forests – An Ecosystem Study. Ed. T
634 Persson.. Ecol. Bull. (Stockholm) 32, 125-138.

635 Freibauer, A., Rounsevell, M.D.A., Smith, P., Verhagen, J., 2004. Carbon sequestration in the
636 agricultural soils of Europe. Geoderma 122, 1 –23.

637 Gonzalez-Quñones, V., Stockdale, E.A., Banning, N.C., Hoyle, F.C., Sawada, Y., Wherret, A.D.,
638 Jones, D.L. and Murphy, D.V., 2011. Soil microbial biomass – Interpretation and consideration
639 for soil monitoring. Soil Res. 49, 287-304.

640 Gratani, L., Varone, L., 2014. Atmospheric carbon dioxide concentration variations in Rome:
641 relationship with traffic level and urban park size. Urban Ecosyst. 17:501–511.

642 Holmes, A., Müller, K., Clothier, B., and Deurer, M., 2015. Carbon Sequestration in Kiwifruit
643 Orchard Soils at Depth to Mitigate Carbon Emissions. Commun. Soil Sci. Plant Anal. 46 (sup1),
644 122-136.

645 Huang, X., Lakso, A.N., Eissenstat, D.M., 2005. Interactive effects of soil temperature and moisture
646 on Concord grape root respiration . J. Exp. Bot. 56 (420), 2651–2660.

647 Ingwersen, J., Butterbach-Bahl, K., Gasche, R., Richter, O., Papen, H., 1999. Barometric process
 648 separation: new method for quantifying nitrification, denitrification, and nitrous oxide sources in
 649 soils. Soil Sci. Soc. Am. J. 63,117–128.

650 IPCC, 2003. Good practice guidance for LULUCF – ANNEX A Glossary.

651 ISTAT, 2011. www.ISTAT.it accession march 2013.

652 Keightley, K.E., 2011. Applying new methods for estimating in vivo vineyard carbon storage .
 653 Am.J.Enol.Vitic. 62, 214-218.

654 Keller, M., Koblet, W., 1995. Dry matter and leaf area partitioning, bud fertility and second season
 655 growth of *Vitis vinifera* L. : Responses to nitrogen supply and limiting irradiance. Vitis 34 (2), 77-
 656 83.

657 Kroodsma, D.A., Field, C.B., 2006 Carbon sequestration in California agriculture, 1980-2000. Ecol.
 658 Appl. Oct;16(5),1975-85.

659 Jones, G., Davis, R., 2000. Using a synoptic climatological approach to Understand climate–
 660 viticulture relationships . Int. J. Climatol. 2, 813–837.

661 Lal, R., 2011. Sequestering carbon in the soils of agro-ecosystems. Food Policy 36, 33-39.

662 Landsberg, J. J., 1980. Limits to apple yields imposed by weather. In: Hurd, R.G., Biscoe, P.V.,
 663 Dennis C. (Eds), Opportunities for Increasing Crop Yields. Pitman Publishing Ltd. London 1979,
 664 pp. 161-180 .

665 Liguori, G., Gugliuzza, G., Inglese, P., 2009. Evaluating carbon fluxes in orange orchards in relation
 666 to planting density . J. Agric. Science 147, 637-645.

667 Lovett, G. M., Cole, J. J., Pace, M.L., 2006. Is Net Ecosystem Production Equal to Ecosystem
 668 Carbon Accumulation? . Ecosystems 9, 152–155.

669 MEA, 2005. Ecosystems and human well-being: synthesis. Millennium Ecosystem Assessment.
 670 – (The Millennium Ecosystem Assessment series) Washington, DC: Island Press; 2005.
 671 ISBN 1-59726-040-1.

672 Morlat, R., Jacquet, A., 1993. The soil effects on the grapevine root system in several vineyards of
 673 the Loire valley (France). *Vitis* 32, 35-42.

674 Moscatelli, M.C., Lagomarsino, A., Marinari, S., De Angelis, P., Grego, S., 2005. Soil microbial
 675 indices as bioindicators of environmental changes in a popular plantation . *Ecol. Indic.* 5, 171–
 676 179.

677 Mullins, M. G., Bouquet, A., Williams, L.E., 1992. Biology of the grapevine. Biology of
 678 Horticultural Crops. Cambridge University Press ISBN 0.521-30507-1.

679 OIV, 2013. Statistical report on world vitiviniculture 2013. www.oiv.int/oiv/files/2013_Report.pdf

680 Poni, S., Palliotti, A., Bernizzoni, F., 2006. Calibration and evaluation of a STELLA Software-based
 681 Daily CO₂ balance model in *Vitis vinifera* L. *J. Amer. Soc. Hort. Sci.* 131 (2), 273-283.

682 Salvati, L., 2013. Monitoring high-quality soil consumption driven by urban pressure in a growing
 683 city (Rome, Italy). *Cities* 31, 349-356.

684 Smart, D., Carlisle, E., Spencer, R., 2007. Carbon Flow Through Root and Microbial Respiration in
 685 Vineyards and Adjacent Oak Woodland Grassland Communities . 2001-2006 Mission Kearney
 686 Foundation of Soil Science: Soil Carbon and California s Terrestrial Ecosystems Final Report:
 687 2001018.

688 Sofo, A., Nuzzo, V., Palese, A.M., Xiloyannis, C., Celano, G., Zukowsky, P., Dichio, B., 2005. Net
 689 CO₂ storage in mediterranean olive and peach orchards. *Sci. Hort.* 107, 17–24.

690 Steenwerth, K., Pierce, D.L., Carlisle, E.A., Spencer, R.G.M., Smart, D.R., 2010. A vineyard
 691 agroecosystem: disturbance and precipitation affect soil respiration under Mediterranean
 692 conditions . *Soil Sci. Soc. Am. J.* 74, 231–239.

693 Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J. et al., 2013. The knowns, known
 694 unknowns and unknowns of sequestration of soil organic carbon. *Agric. Ecosyst. Environ.* 164,
 695 80– 99.

696 Tonietto, J., Carbonneau, A., 2004. A multicriteria climatic classification system for grape growing
 697 grape growing regions worldwide . *Agric. For. Meteorol.* 124 (1-2), 81-97.

698 Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method fro measuring microbial
699 biomass C. Soil Biol. Biochem. 19, 703-707.

700 Viers, J.H., Williams, J.N., Nicholas, K.A., Barbosa, O., Kotzé, I., Spence, L., Webb, L.B.,
701 Merenlender, A., Reynolds, M., 2013. Vinecology: pairing wine with nature. Conserv. Lett.,
702 6, 287–299. doi: 10.1111/conl.12011

703 Vogt, K.A., Vogt, D. J., Bloomfield, J., 1998. Analysis of some direct and indirect methods for
704 estimating root biomass and production of forests at an ecosystem level. Plant Soil 200, 71–89.

705 Whittaker, R. H., Woodwell, G. M., 1968. Dimension and Production Relations of Trees and Shrubs
706 in the Brookhaven Forest, New York. J. Ecol. 56 (1), 1-25.

707 Published by [British Ecological Society](http://www.jstor.org/stable/2258063) (http://www.jstor.org/stable/2258063)

708 Williams, J.N., Hollander, A.D., O Geen, A.T., Thrupp, L.A., Hanifin, R., Steenwerth, K.,
709 McGourty, G., Jackson, L.E., 2011. Assessment of carbon in woody plants and soil across a
710 vineyard-woodland landscape. Carbon Balance Manag. 6 (1).

711 Williams, A., Hedlund, K., 2013. Indicators of soil ecosystem services in conventional and organic
712 arable fields along a gradient of landscape heterogeneity in southern Sweden. Appl. Soil Ecol. 65,
713 1– 7.

714 **Tables**

715 Table 1 – Agronomic management of three vineyard case studies. Information refers to two environments (natural and
716 peri-urban grape growing area) and two management regimes (organic vs conventional farming).

717

CULTURAL PRACTICES	NATURAL GRAPE GROWING AREA		PERI-URBAN GRAPE GROWING AREA
	ORGANIC	CONVENTIONAL	CONVENTIONAL ⁽²⁾
Soil management	Interrow sward alternating with an adjacent plowing and tilled interrow soil. No herbicide treatment. Three soi tillage per year.	Interrow sward alternating with an adjacent plowing and tilled interrow soil. Herbicide treatment and no-tillage soil management.	Interrow sward alternating with an adjacent plowing and tilled interrow soil. Herbicide treatment. Three soil tillage per year.
Fertilizer	Manure	Chemical	Chemical
Vineyard pruning residues	Burying of pruning residues. One soil tillage per year.	Burying of pruning residues. One soil tillage per year.	Burying of pruning residues. One soil tillage per year.

718 ^(a) In conversion from organic to conventional since 2010.

719

720

721

722

723 Table 2 - Bioclimatic indexes of the two grape growing area case studies. IW, Winkler index; IH, Huglin index; CI, cool
724 index. Absolute, mean values and significance between seasons (*ns*, not significant; *, *P* <0.05; **, *P* <0.01).

725

Climate index	Natural grape growing area				Peri-urban grape growing area			
	Mean 2004-201	201	201		Mean 2004-201	201	201	
IW	204	226	234	**	233	222	229	**
IH	258	279	283	*	276	273	274	*
CI	1	1	1	*	1	1	1	*
Days T°C > 30°C	8	10	9	<i>ns</i>	9	8	8	<i>ns</i>
Mean rainfall	83	49	77	<i>ns</i>	84	72	74	<i>ns</i>

726

727

728

729

730

731

732

733

734

735

736

737

738

739

740

741

742 Table 3 – Total carbon fixation in the vineyard (5600 vines ha⁻¹) under different environmental conditions (natural vs
743 peri-urban grape growing area) and different management systems (organic vs conventional farming). The contribution of
744 grapevine organs is reported for the two examined growing seasons (2011, 2012). Data were collected on 6 replicates per
745 vineyard.

746

Vineyard management	Natural grape growing area				Peri-urban grape growing area	
	Conventional		Organic		Conventional	
Year	2011	2012	2011	2012	2011	2012
	(tC ha ⁻¹ years ⁻¹)		(tC ha ⁻¹ years ⁻¹)		(tC ha ⁻¹ years ⁻¹)	

Grapevine Organs

Leaves	0.78 ± 0.01	1.94 ± 0.01	1.14 ± 0.01	1.42 ± 0.02	1.06 ± 0.02	1.73 ± 0.01
Lateral Shoots ^(z)		0.95 ± 0.03		0.66 ± 0.07	0.53 ± 0.15	0.52 ± 0.06
Annual Wood	1.94 ± 0.32	2.28 ± 0.58	2.33 ± 0.73	1.84 ± 0.32	0.70 ± 0.13	1.71 ± 0.31
Bunches	1.82 ± 0.75	1.38 ± 0.49	1.61 ± 0.72	1.16 ± 0.37	2.62 ± 0.55	2.93 ± 0.61
Roots	0.75 ± 0.01	0.71 ± 0.01	0.46 ± 0.03	0.38 ± 0.01	1.70 ± 0.39	1.14 ± 0.01
Tota	5.29 ± 1.09	7.26 ± 1.11	5.67 ± 1.46	5.1 ± 0.77	6.61 ± 1.23	8.01 ± 0.99

^(z) Removed by summer canopy pruning

Table 4 - Dry matter partitioning among grapevine organs. Data refer to two environments (natural and peri-urban grape growing area) and two management regimes (organic vs conventional farming) in two observed seasons (2011 and 2012). Significance between seasons has reported (**, P < 0.01; ***, P < 0.001). Data were collected on 6 replicates per vineyard.

Vineyard management	Yea	Natural grape growing area				Peri-urban grape growing area			
		Conventional		Organic		Conventional			
		2011	2012	2011	2012	2011	2012		
<i>Grapevine Organs</i>									
Leaves		15%	27%	**	20%	25%	**	16%	22%
Lateral Shoots ^(z)			13%	**		15%	**	8%	6%
Annual Wood		37%	31%	***	41%	32%	***	11%	21%
Bunches		34%	19%	**	28%	20%	**	40%	37%
Roots		14%	10%	**	11%	9%	**	26%	14%
Tota		100%	100%	**	100%	100%	**	100%	100%

^(z) Removed by summer canopy pruning

756

757 Table 5 – Soil functionality indicators (physical indicators: clay, silt and sand; chemical indicators: pH, nitrogen (N) and

758 Total Organic Carbon (TOC); microbiological indicators: Microbial biomass carbon (MBC), Basal (Rb) and Cumulative

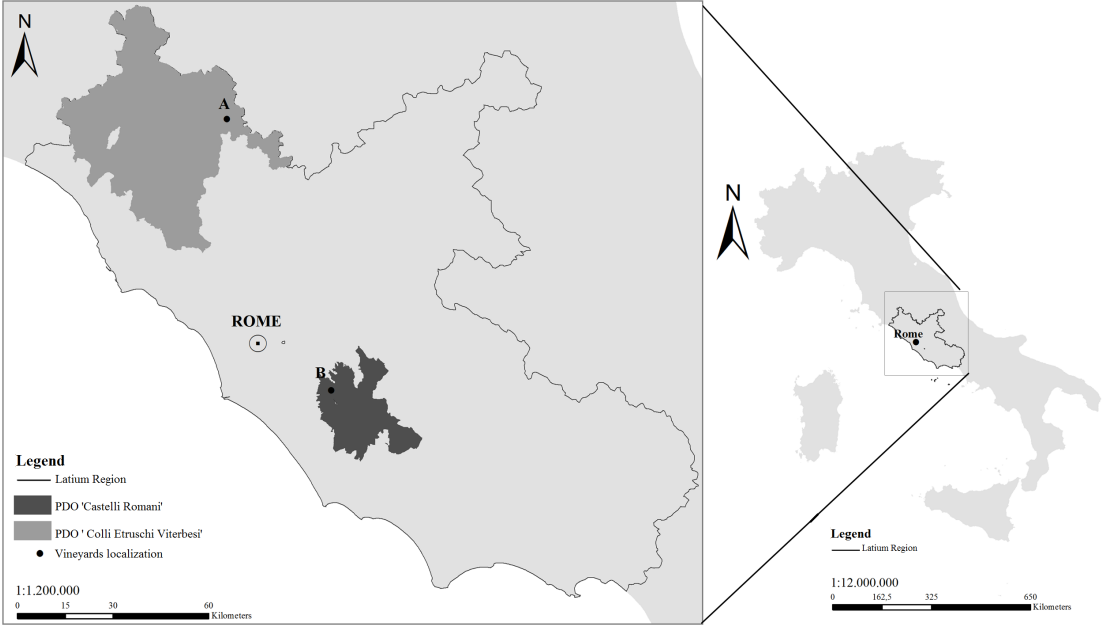
759 Respiration (Rcum), and functionality indicators (metabolic quotient (qCO_2), carbon Mineralization quotient (qM) and

760 microbial biomass TOC ratio (MBC/TOC)). Data refer to two environments (natural and peri-urban grape growing area)

761 and two management regimes (organic vs conventional farming).

762

763



764

765

766

767 Figure 1 – Two traditional grape-wine growing areas in Latium region: the Protected Designation of

768 Origin (PDO) Colli Etruschi Viterbesi, northern of Rome, and the PDO Castelli Romani, southern of

769 Rome. The circles indicate the position of the vineyard case studies. A, position of the conventional

770 and organic vineyards in the natural grape growing area; B position of the conventional vineyard in

771 the peri-urban grape growing area.

cv Merlot / berlandieri x rupestris

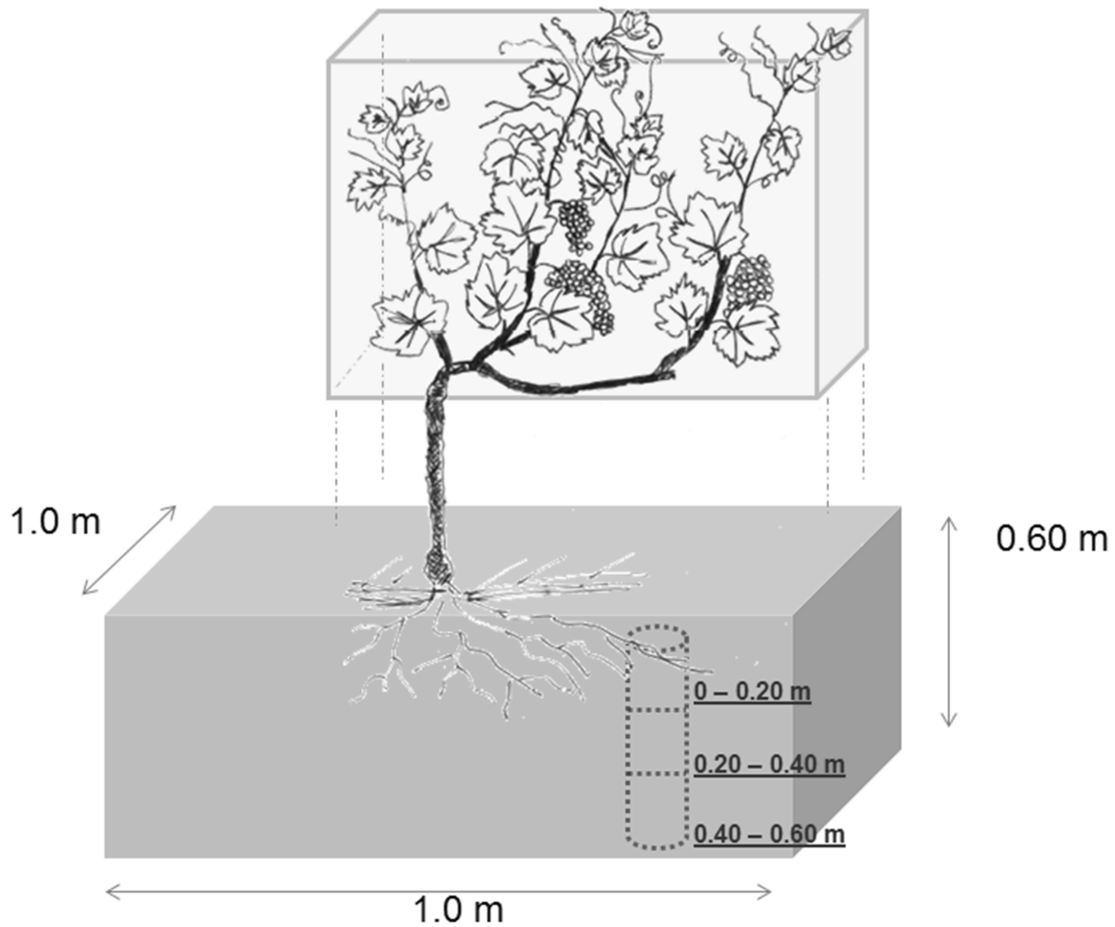


Figure 2 – Carbon sink model for the above- and below-ground biomass determination in grapevine (*Vitis vinifera* sativa L.) cv Merlot/ *berlandieri* x *rupestris*. The model is based on a explored soil volume of 0.6 m³, according to the planting distances (0.80 x 2.3m) and the supposed root system distribution beyond the above-ground canopy projection. Dotted cylinder represents the ingrowth core-system posed at the distance of 0.50 m from vine trunk.

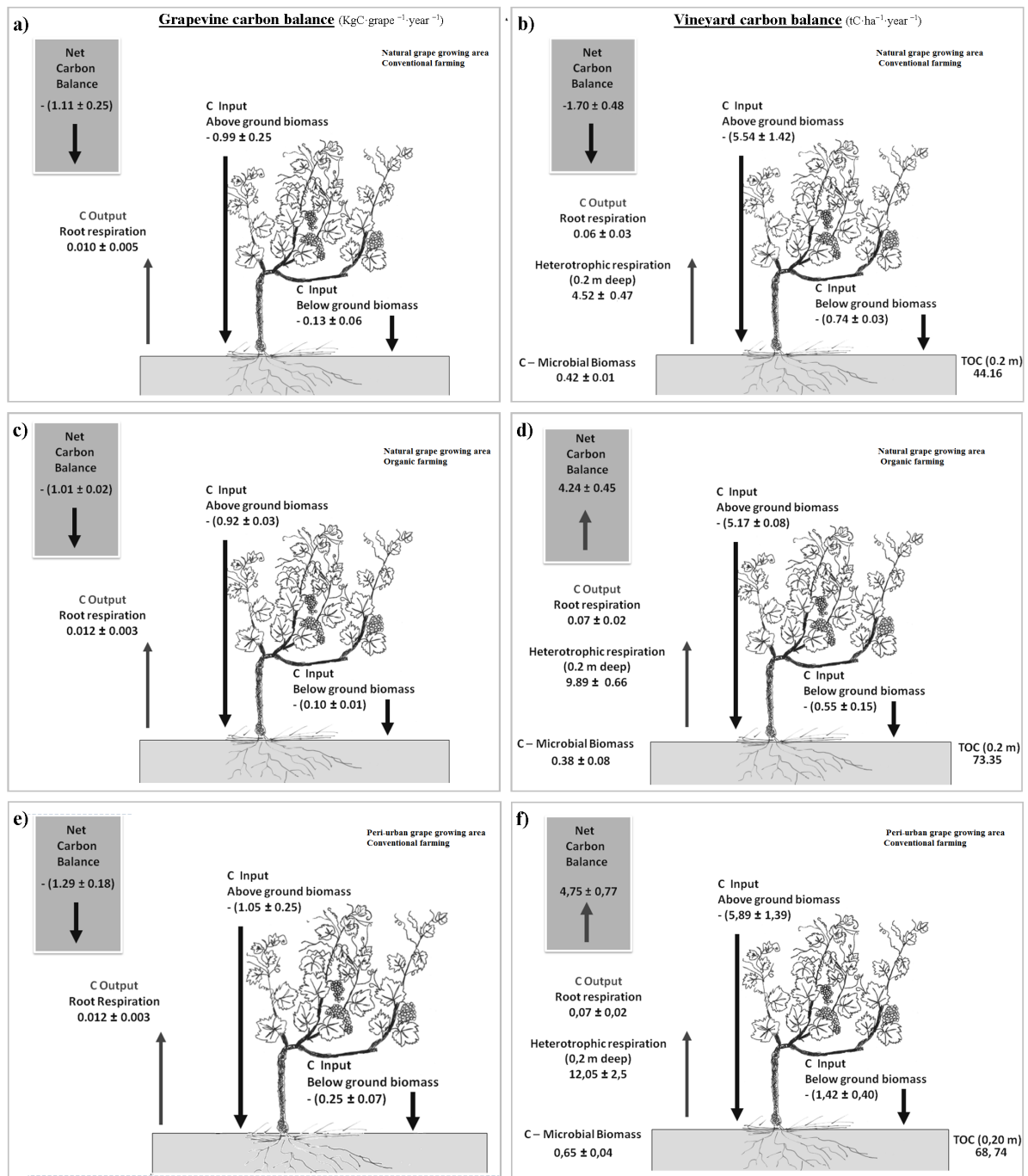


Figure 3 – Grapevine (cv Merlot / *berlandieri* x *rupestris*) (left a,c,e) and vineyards carbon balance (5600 vine/hectare) (right b,d,f) in the two study areas (natural and peri-urban growing area, northern and southern of Rome respectively), under different management regimes (conventional vs organic farming).

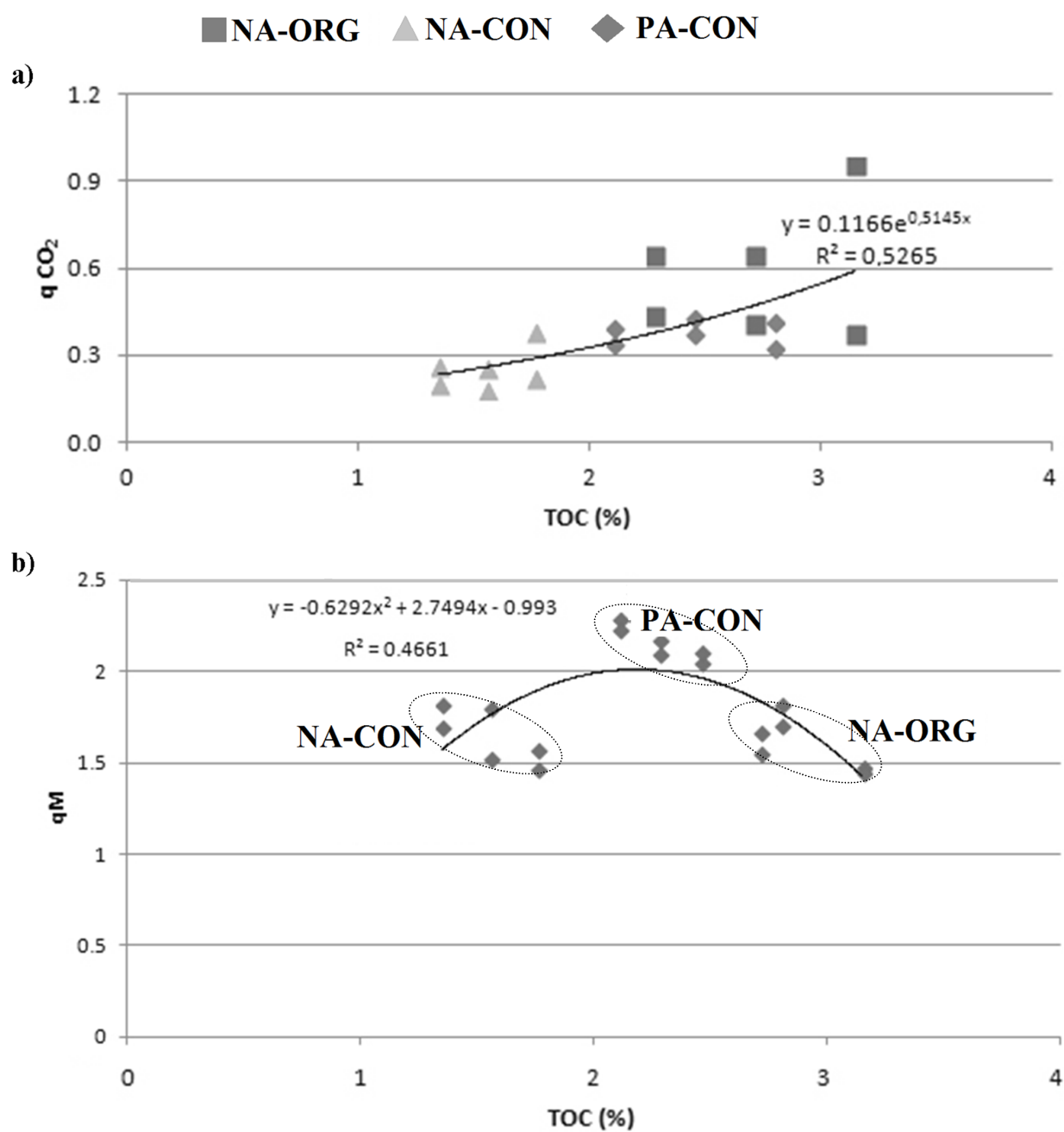


Figure 4 – PCA of a set of soil functional indicators in the three vineyard case studies. NA-ORG : Natural Area, Organic farming; NA-CON: Natural Area, Conventional farming; PA-CON: Peri-urban Area, Conventional farming.

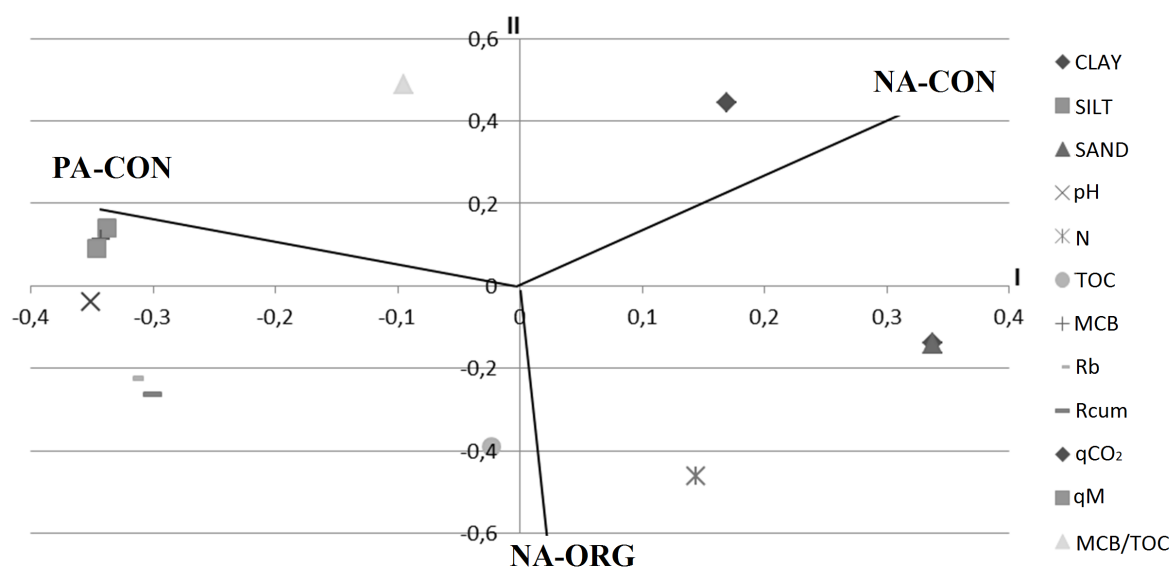


Figure 5 –Correlation between different soil functional indicators: (a) qCO₂ and TOC (%); (b) qM and TOC (%). Data refer to soil samples from vineyard in two environments (natural and peri-urban grape growing area) under different management systems (organic farming, vs conventional farming). NA-ORG: Natural Area, Organic farming; NA-CON: Natural Area, Conventional farming; PA-CON: Peri-urban Area, Conventional farming.