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1 **Conventional *versus* organic management: application of simple and complex indexes to assess**
2 **soil quality**

3 Martina Mazzon^{1*}, Luciano Cavani¹, Claudio Ciavatta¹, Gabriele Campanelli², Giovanni Burgio¹, Claudio
4 Marzadori¹

5 ¹ Department of Agricultural and Food Sciences - *Alma Mater Studiorum* University of Bologna, Bologna (BO), Italy

6 ² Council for Agricultural Research and Economics – Research Centre for Vegetable and Ornamental Crops (CREA-OF),
7 Monsampolo del Tronto (AP), Italy

8 *Corresponding author: Martina Mazzon, martina.mazzon2@unibo.it

9

10 **Abstract**

11 Organic management aims to maintain and/or enhance the soil quality by adopting crop rotation, reduced
12 tillage, and application of organic fertilizers. Several studies highlight the advantages of organic
13 management in terms of soil quality and soil fertility, the key themes in sustainable agronomy. The aim
14 of this study was to understand whether there were differences in soil quality between two different
15 approaches of organic management. Soil quality was assessed using a set of biochemical parameters
16 individually or in combination, in simple and complex indexes, respectively. Soil samples were procured
17 from a long-term field experiment area located in Monsanpolo del Tronto (Central Italy) in which
18 conventional (Conv), and two different organic managements (Org1, organic traditional; Org2, organic
19 agroecological) were followed, and were assessed for soil quality. Results from individual soil properties,
20 simple and complex indexes highlighted that Conv and Org1 were similar in terms of acquisition activity
21 indicating that both mineral and organic fertilizers supply C, N, and P equally to agro-ecosystems.
22 However, in Org2, despite theoretical imbalances in terms of C:N:P, microbial activity efficiently filled
23 this imbalance without affecting soil organic carbon content. The indexes showed a positive metabolic
24 response and a higher soil quality in both the organically managed plots, indicating that organic
25 management, independent of the agronomic approach, maintains the soil quality despite the differences

26 in biochemical processes. Moreover, simple and complex soil quality indexes were sensitive enough to
27 discriminate the two organic management strategies.

28

29

30 *Keywords:*

31 soil functionality; agronomic management; strip cropping; enzyme activities; biochemical indexes

32

33 *Highlights:*

- 34 • Conventional and organic management effects on soil quality were evaluated
- 35 • Soil organic C and microbial biomass were enhanced by the organic managements
- 36 • Specific hydrolytic enzyme activities increased in the conventional management
- 37 • Soil quality indexes highlight differences between the two organic managements
- 38 • Soil quality indexes help in understanding the soil biochemical processes

39 **Introduction**

40 Agriculture is moving from conventional to more sustainable soil management with a 102% increase in
41 organic managed areas from 1999 to 2019 globally (IFOAM and FiBL, 2021) and a 46% increase from
42 2012 to 2019 in the European Union (Eurostat, 2020). Indeed, intensive tillage leads to degradation of
43 ecosystems through soil erosion, water contamination, deforestation, desertification and, consequently,
44 to loss of productivity (Edwards et al., 1993; Garini et al., 2017). In contrast, sustainable agriculture is
45 based on integrated systems of agricultural production with minimum dependence upon high inputs of
46 energy, that should maintain – or only slightly decrease – productivity and protect the environment from
47 soil and food contamination, preserve ecological diversity, and maintain and/or improve soil quality and
48 fertility (Edwards et al., 1993; Francis and Wezel, 2015). Therefore, the major challenge is to identify safe
49 and secure methods to produce food, while reducing the negative impacts of agriculture on the
50 environment (Dupré et al., 2017).

51 Organic management aims to achieve the required yield while maintaining soil quality by the adoption of
52 crop rotation with cover crops, reduced tillage (Hartmann et al., 2015; Tilman et al., 2002), and the
53 application of organic fertilizers such as animal and green manures, and off-farm organic wastes
54 (Drinkwater et al., 1995). Moreover, organic agriculture contributes to global food supply (Luo et al.,
55 2019; Sandhu et al., 2010) although the yields obtained are usually lower than in conventional agriculture
56 (Bonanomi et al., 2016; De Ponti et al., 2012). Soil quality and fertility not only affect productivity and
57 mineral nutrition, but also determine the biological equilibrium and regulation of agroecosystems
58 (Lemanceau et al., 2014). Several studies have been conducted to compare the effects of organic and
59 conventional management strategies on soil quality and fertility. Results from studies conducted in
60 Central Italy and Spain (temperate areas characterized by different soil textures and pH range between
61 6.8–7.8) highlight that in both arable and orchard systems, organic agriculture, characterized by the
62 application of compost, manure, or crop residues, induced a higher soil organic carbon (SOC) content
63 (10–50%) and higher microbial (enzymatic) activity (~30%) compared to conventional agriculture (Baldi
64 et al., 2018; García-Ruiz et al., 2008; Marinari et al., 2006; Mazzon et al., 2018; Plaza et al., 2012). Braman

65 et al. (2016), in a study conducted in Canada on a clay soil with a pH of 7.4, and Chavarria et al. (2018),
66 in a study conducted in Argentina on a silt loam soil with a pH of 5.8, demonstrated lower values of the
67 soil metabolic quotient (qCO_2 , a metabolic efficiency index determined by the ratio between soil
68 respiration and microbial biomass carbon content) in organic management, thus suggesting a high
69 efficiency of using organic carbon (C) sources under this management. Kwiatkowski et al. (2020), in an
70 experiment comparing organic and conventional management on a silt loam soil with a pH of 6.5 in
71 Poland, found higher SOC and total nitrogen (TN) contents as well as a higher soil pH in the organic
72 system compared to the conventional one. Moreover, worldwide studies and meta-analyses comparing
73 organic and conventional managements (Drinkwater et al., 1995; Luo et al., 2019), including analysis of
74 soil tillage intensity (Laudicina et al., 2011; Roldán et al., 2005), and of N dynamics from mineral and
75 organic fertilization (Toselli et al., 2019), highlight the advantages that organic management provides in
76 term of sustainability, soil quality and soil fertility.

77 Several soil chemical and biochemical indicators are useful in determining the soil quality: chemical (pH,
78 organic C, total N, and available P), physical (texture, bulk density, and water retention) and biological
79 (microbial activity and biomass) (Bünemann et al., 2018). However, it is noteworthy that soils react slowly
80 to changes in management; therefore, in assessing soil quality, the identification of an appropriate and
81 sensitive set of soil attributes is an important step (Bünemann et al., 2018). For example, physical soil
82 properties are certainly important in soil quality determination but they are considered “slow-changes”
83 indicators, while biochemical properties are considered “dynamic” indicators connected to soil
84 functionality and dynamics in relation with the nutrient acquisition processes (Bünemann et al., 2018;
85 Muñoz-Rojas, 2018). Within the biochemical indicators, the soil enzymatic activities are considered to be
86 sensitive and early indicators of changes in soil quality (Gil-Sotres et al., 2005; Nannipieri et al., 2018,
87 2002; Sinsabaugh et al., 2008). Indeed, they are natural catalysts for many important soil processes, such
88 as organic matter decomposition, nutrient release, molecular N fixation, and C, N, and other major
89 nutrient cycles (Balota et al., 2004; Kwiatkowski et al., 2020; Wallenstein et al., 2012). Nonetheless, it is
90 inappropriate to consider a single enzymatic activity as an index of soil quality or soil fertility, which

91 depends on many soil reactions and properties (Gil-Sotres et al., 2005; Nannipieri et al., 2002; Nannipieri
92 et al., 2018). Gil-Sotres et al. (2005) delineated three approaches in using soil biochemical parameters to
93 estimate soil quality: (i) individual properties, (ii) simple indexes derived from the relationship between
94 two individual properties, and (iii) complex indexes derived from the combinations of different properties
95 or on the basis of statistical procedures. Individual properties could be, for example, SOC, microbial
96 biomass, nitrogen mineralization, soil respiration, and dehydrogenase activity. However, individual
97 properties could return contradictory results, and being the expression of specific soil processes, they
98 cannot reflect many of the reactions which determine soil quality. Therefore, simple indexes could
99 overcome the constraints of individual properties and fulfil the requirements of a good indicator (Gil-
100 Sotres et al., 2005). The four most frequently used simple indexes are the specific enzyme activities (the
101 ratio of soil enzymatic activities to the microbial biomass), the metabolic quotient (the ratio of soil basal
102 respiration to the soil microbial biomass, qCO_2), the microbial quotient (the ratio of microbial C to the
103 total organic C), and the metabolic index (the ratio of dehydrogenase activity to the extractable organic
104 C, MI). Nevertheless, simple indexes possess limitations in terms of soil quality definition, as they do not
105 have reference levels, and their responses are not always easy to relate to specific soil modification
106 processes. Complex indexes evaluate the soil quality by combining different biochemical properties such
107 as the biological fertility index, the enzymatic activity number, the lignocellulosic factor of Sinsabaugh et
108 al. (1994), and the geometric mean of enzyme activities. Other complex indexes are obtained by applying
109 statistical techniques to combine the biochemical properties (Gil-Sotres et al., 2005) and thus, the use of
110 complex expressions or statistical procedures can appropriately describe the complexity of soil systems.
111 In this study, as complex indexes, we focused on the ecosystem ratios of C:N, C:P and N:P acquisition
112 activity and the soil management assessment framework (SMAF). The ecosystem ratios are given by the
113 natural logarithm of enzyme activities involved in C, N, and P cycles, and are a measure of the enzymatic
114 resources directed to the acquisition of organic P and organic N relative to C (Sinsabaugh et al., 2008).
115 The soil management assessment framework (hereafter in the text SQI – Soil Quality Index) aims to
116 evaluate the soil quality using a minimum dataset chosen from a larger dataset that includes physical,

117 chemical, and biological soil properties (Andrews and Carroll, 2001). We chose these two complex
118 indexes as they satisfy the majority of the characteristics for a good indicator: they measure one or more
119 soil functions, are sensitive and respond quickly to changes in soil management, and are easy to obtain
120 and interpret.

121 The use of biochemical indexes to assess soil quality is not novel, although their practical application in
122 field experiments is more recent. However, Bunemann et al. (2018) stressed that an overall SQI, even if
123 desirable, must be cautiously used to assess soil quality only in relation to specific soil functions. In
124 addition, the sensitivity of selected indexes to evaluate the soil quality in different ecosystems and the
125 ability to discriminate between different soil management systems is debatable. Nowadays, for example,
126 different organic management systems have been developed, and we need affordable procedures to
127 evaluate their strengths and weaknesses.

128 In light of the above, a long-term field experiment in a Mediterranean area (Marche Region, Italy), with
129 conventional and two different organic managements, was performed to understand whether there are
130 differences in soil quality between the different management strategies. Specifically, we asked: *i)* Do the
131 organic managements always lead to better soil quality compared to the conventional management? *ii)*
132 Do the soil biochemical indexes differ between the two organic management approaches? *iii)* Can soil
133 quality indexes help us to understand the soil biochemical processes under different organic management
134 strategies?

135

136 **Material and Methods**

137 **Area of study**

138 The investigations were conducted at the Council for Agricultural Research and Economics – Research
139 Centre for Vegetable and Ornamental Crops (CREA-OF) in Monsampolo del Tronto, Marche Region,
140 (latitude 42°53' N, longitude 13°48' E). The climate of the locality is classified as thermo-Mediterranean,
141 characterized by mild–cool winters and hot summers with cumulative annual precipitation and mean

142 annual temperature (in 2018) of 789 mm and 15.7 °C, respectively. The soil is classified as Typic
143 Calcixerepts fine-loamy, mixed thermic (USDA, 1996) (USDA Soil Taxonomy, 2006).
144 The experimental design included three experimental areas: two were within an organic field managed
145 since 2001, according to European legislation for organic farming, and one was within a neighboring
146 conventional field. Three agronomic management strategies for tomatoes (*Solanum lycopersicum* L.) were
147 studied: Org1 (organic traditional), Org2 (organic agroecological) and Conv (conventional).
148 Descriptions of the agronomic practices for each management are provided in Table 1. The Org2
149 management is part of the MOnsampolo VEgetable (MOVE) organic long-term field experiment and is
150 characterized by a four-year crop rotation (Campanelli and Canali, 2012). In particular, the in-line roller-
151 crimper technique (Canali et al., 2013) was used for flattening strips of faba bean (*Vicia faba* L.) after fresh
152 pod harvest. In this way, a conservation tilling strategy and strip cropping cultivation of tomato for the
153 fresh market and faba bean for dry grain harvest was realized. The measurements were conducted on a
154 surface area of 176 m² for each experiment. In June 2018, from the plot of each management, during
155 tomato-growing season, soil samples from the top 20 cm soil profile were taken along the tomato rows,
156 for a total of 24 soil samples (8 per plot). In each plot, the external rows were not sampled to avoid
157 border effects owing to neighboring crops. Fresh samples were immediately kept in a cooler for
158 transportation to the laboratory where they were sieved to 2 mm; roots and plant residues were carefully
159 removed using forceps. Samples were then homogenized and divided into two aliquots: one was air-dried
160 and the other was stored in plastic bags at 4 °C.

161

162 **Soil chemical and biochemical analysis**

163 Soil pH was measured in ultrapure water (ISO 10390, 2005). SOC and total N (TN) were analyzed using
164 an elemental analyzer (Flash 2000; Thermo Fisher Scientific, USA). Soil microbial biomass C (MBC) and
165 N (MBN) were determined using the chloroform-fumigation extraction method (Vance et al., 1987), and
166 the potassium sulfate extracts were analyzed using an elemental analyzer (TOC - TN Hypertoc; Shimadzu
167 Corp., Kyoto, Japan). MBC was calculated as the difference in organic C between the fumigated and

168 unfumigated soil extracts. The organic C content of the unfumigated extracts was used as an estimation
169 of soil extractable C (DOC, dissolved organic C); similarly, MBN and soil extractable N (TDN, total
170 dissolved N) were calculated.

171 Available phosphorous (P_{Olsen}) was determined according to Olsen method (Olsen et al., 1954) using a
172 spectrophotometer (Jasco V-530 UV/VIS Spectrophotometer; JASCO Corporation, Japan) at $\lambda = 882$
173 nm. P_{Olsen} content was expressed as $\text{g kg}_{\text{ds}}^{-1}$. Soil basal respiration rate (SBR) was determined according
174 to Isermeyer (1952) and expressed as mg of C-CO₂ produced per kg of dry soil during the incubation
175 time ($\text{mg C-CO}_2 \text{ kg}_{\text{ds}}^{-1} \text{ h}^{-1}$).

176

177 **Soil enzymatic activities**

178 The activities of eight extracellular enzymes and one intracellular enzyme were measured (Table S1). Six
179 extracellular hydrolytic enzyme activities were determined using fluorogenic 4-methylumbelliferyl (MUF)
180 conjugates according to Giacometti et al. (2014) in the equivalent of 2 g of dried soil. The 96-well
181 microplates were incubated in the dark at 30 °C and fluorescence was measured using a microplate
182 fluorometer (Infinite® 200; TECAN, Männedorf, Switzerland) with λ at 365 nm and 450 nm for
183 excitation and emission, respectively. The microplates were shaken for 5 s before each reading and
184 measurements were recorded immediately after the plate setup and at intervals of 30 min, for a duration
185 of 3.5 h. The activity was expressed as $\text{nmol MUF g}_{\text{ds}}^{-1} \text{ h}^{-1}$. Measurements for the following oxidative
186 enzymes were performed spectrophotometrically (Jasco V-530 UV/VIS Spectrophotometer; JASCO
187 Corporation, Japan).

188 Dehydrogenase activity (Dehy) was measured as described by Von Mersi and Schinner (1991). Released
189 iodo-nitrotetrazolium formazan (INTF) was measured at $\lambda = 464$ nm and the activity was expressed as
190 $\text{nmol INTF g}_{\text{ds}}^{-1} \text{ h}^{-1}$. Laccase activity (Lac) was determined as described by Floch et al. (2007), and the
191 reaction product, 2,2'-azinobis-(3-ethylbenzothiazoline-6-sulfonate) (ABTS⁺), was measured at $\lambda = 420$
192 nm. The activity was calculated using a molar extinction coefficient of $18460 \text{ L mol}^{-1} \text{ cm}^{-1}$ and expressed
193 as $\mu\text{mol ABTS}^+ \text{ g}_{\text{ds}}^{-1} \text{ min}^{-1}$. Tyrosinase activity (Tyr) was measured as described by Sinsabaugh et al.

194 (1999). The absorbance was measured at $\lambda = 475$ nm, and the activity was calculated using a molar
195 extinction coefficient of $3700 \text{ L mol}^{-1} \text{ cm}^{-1}$ and expressed as $\mu\text{mol DOPA g}_{\text{ds}}^{-1} \text{ h}^{-1}$.

196

197 **Simple soil quality indexes**

198 The following simple indexes were determined: the metabolic quotient ($q\text{CO}_2$), calculated by dividing the
199 SBR by the MBC and expressed as $\text{mg C-CO}_2 \text{ g}_C^{-1}$, represents the quantity of substrate mineralized per
200 unit of microbial biomass, per unit of time (Gil-Sotres et al., 2005), and indicates the usage efficiency of
201 C sources (Anderson and Domsch, 1993; Bastida et al., 2008); the metabolic index (MI), obtained by
202 dividing the Dehy by the DOC and expressed as $\mu\text{mol INTF g}_C^{-1} \text{ h}^{-1}$ (Masciandaro et al., 1998), connects
203 the possible C availability for microbial metabolism with the microbial activity (Bastida et al., 2008); and
204 the specific soil enzymatic activities (Gil-Sotres et al., 2005; Kandeler and Eder, 1993; Trasar-Cepeda et
205 al., 2008), calculated by dividing the enzymatic activity values with the MBC; an increase may be due to
206 more enzyme production, more release of enzymes immobilized in clays or humic colloids (Kandeler and
207 Eder, 1993), or an increase in substrate available for enzymatic activity (Bastida et al., 2008).

208

209 **Complex soil quality indexes**

210 Complex soil quality indexes as ecosystem ratios and SQI were calculated. The ecosystem ratios were
211 determined using the natural logarithm of the soil enzymatic activities involved in C, N, and P cycles,
212 thus determining the C:N (C:N_{enz}), C:P (C:P_{enz}) and N:P (N:P_{enz}) acquisition activity (Sinsabaugh et al.,
213 2008); for example, the C:N_{enz} was obtained by dividing the $\ln(\beta_{\text{glu}} + \alpha_{\text{glu}} + \beta_{\text{cel}} + \beta_{\text{xyl}})$ by the $\ln(\text{NAG})$.
214 The SQI was determined using a process (Fig. 1) that included i) indicator selection, ii) indicator scoring
215 and iii) integration of the scores into the index. Briefly, the minimum dataset (MDS) was selected from
216 the principal component analysis (PCA), in which the principal components (PC) with eigenvalues ≥ 1
217 and the properties with highest loadings were assumed to best represent the system. The correlation was
218 then used to reduce the redundancy between parameters and only the parameters that did not correlate
219 with each other were selected. Each selected parameter was standardized to a value between 0 and 1 using

220 functions such as “more is better”, “less is better”, or “optimum” depending on the variables. Specific
221 enzymatic activities were included and standardized using the function “less is better”. Finally, SQI was
222 calculated using the “weighted additive” equation (Eq. 1) that comprises the sum of the scores (S_i) of the
223 MDS multiplied by the amount of variation (W_i) in the corresponding PC. In general, higher SQI values
224 correspond to higher soil quality (Andrews et al., 2002, 2004; Andrews and Carroll, 2001; Askari and
225 Holden, 2015). (Andrews et al., 2004, 2002; Andrews and Carroll, 2001; Askari and Holden, 2015)

$$226 \quad SQI = \sum_{i=1}^n W_i S_i \quad (\text{Eq. 1})$$

227

228 **Statistical analysis**

229 Data were analyzed with the Kruskal-Wallis nonparametric test ($\alpha < 0.05$) and multiple comparisons were
230 performed using Dunn’s test ($\alpha < 0.05$). PCA was performed as a multivariate analysis of data (C and N
231 pools, available P, and enzymatic activities) using the “princomp” function. PCA was performed (C and
232 N pools, available P, and specific enzymatic activities) as the first step for the determination of SQI.
233 Finally, Pearson correlation was conducted on all the considered parameters and indicators (Table S2).
234 All statistical analyses were performed using R software (R Core Team, 2020).

235

236 **Results**

237 **Soil chemical and biochemical analysis**

238 Soil pH showed a slight increase over time (it was 7.8 in 2001) and was significantly affected by
239 management, with a slight increase in Org2 (Table 2). The SOC and TN content (Table 2) showed the
240 same trend with a significant increase in the order Conv < Org2 < Org1. SOC and TN increased by 15–
241 37% and 10–37%, respectively, in Org1 compared to Conv and Org2 management. Both Conv and Org1
242 promoted DOC and TDN content (+16% and +42%, respectively) compared to Org2 management
243 (Table 2). The DOC:TDN ratio (Table 2) showed values increasing in the order Org1 < Conv < Org2.
244 In contrast, MBC (Table 2) was enhanced in Org2 (+29%) and Org1 (+23%) compared to Conv.
245 Although a similar trend was observed for MBN (+19% and +10% with Org2 and Org1, respectively),

246 the differences were not statistically significant (p -value = 0.570) (Table 2). No significant differences (p -
247 value > 0.05) were observed in MBC:MBN, SBR, and P_{Olsen} (Table 2).

248

249 **Soil enzymatic activities**

250 The activities of β -glucosidase, β -xylosidase, β -cellobiosidase and N-acetyl- β -glucosaminidase were
251 significantly higher (with p -value < 0.05) in Org1 (+35%, +28%, +57%, and +33%, respectively) (Fig.
252 2). A similar trend was observed for α -glucosidase activity (+15%), but the differences were not
253 statistically significant (p -value = 0.444) (Fig. 2B). Phosphomonoesterase activity significantly (p -value =
254 0.002) increased in both Org1 (+26%) and Org2 (+36%) management compared to Conv (Fig. 2F).
255 Dehydrogenase activity (Fig. 2G) was higher in Org2 (+15% compared to Org1 and +36% compared to
256 Conv). A similar trend was observed for laccase activity (Fig. 2H) which increased by 18% and 48% in
257 Org2 compared to Org1 and Conv, respectively. However, tyrosinase activity (Fig. 2I) was higher in Conv
258 (+23% compared to Org1 and +14% compared to Org2).

259

260 **Simple soil quality indexes**

261 The $q\text{CO}_2$ decreased while the MI increased in the order Conv - Org1 - Org2 (Table 3), with Conv
262 showing +21% in the $q\text{CO}_2$ and -38% in the MI values with respect to the average mean of Org1 and
263 Org2. The specific hydrolytic enzyme activities (Table 3) of β -glucosidase, α -glucosidase, N-acetyl- β -
264 glucosaminidase, and β -xylosidase were lower in Org2, while phosphomonoesterase showed no
265 differences between the managements, and β -cellobiosidase showed lower activity for both Conv and
266 Org2 management. Among the oxidative specific enzymatic activities, only tyrosinase activity was
267 significantly (p -value = 0.034) different between managements, with higher values in Conv (+65%).

268

269 **Complex soil quality indexes**

270 The C:N ecosystem ratio (Fig. 3A) increased in the order Conv < Org1 < Org2, while the C:P and N:P
271 ecosystem ratios (Fig. 3B, 3C) showed the opposite result, with lower values in Org2 (-11% and -18%,

272 respectively). The SQI (Fig. 3D) was characterized by a minimum dataset composed of specific activities
273 of NAG and Dehy, TN, TDN and MI. The final index highlighted the lower SQI in Conv, with no
274 significant differences between Org1 and Org2.

275

276 **Principal Component Analysis**

277 PCA was performed on C and N pools, available P, and specific enzyme activities for the three
278 management strategies considered. The first two PCs accounted for 42% and 20% of the total variance,
279 respectively (Fig. 4). Conv was distinct from both Org1 and Org2, and characterized by different
280 parameters. Moreover, a slight clustering was observed between the two organic managements. However,
281 focusing on the comparison between Conv and Org, the latter was characterized by SOC, TN, P_{Olsen} ,
282 microbial biomass (MBC and MBN), and specific activities of Lac, PME, β -glu, and β -cel, while the
283 specific activities of Tyr and α -glu defined the former.

284

285 **Discussion**

286 **Conventional vs traditional organic management (Org1)**

287 Soil chemical and biochemical parameters were significantly affected by the different management
288 strategies. As observed in previous studies (Baldi et al., 2018; García-Ruiz et al., 2008; Marinari et al.,
289 2006; Mazzon et al., 2018; Plaza et al., 2012), also in this work SOC content increased with the organic
290 management following the trend Conv ($< \text{Org2}$) $< \text{Org1}$. This difference between Conv and Org1 was
291 mainly because Org1 management involves the addition of organic fertilizers, which could increase SOC
292 content. This was previously observed also in other studies where manure increased SOC content by 35–
293 50% compared to mineral fertilization (Giacometti et al., 2014; Plaza et al., 2012). In the Conv-managed
294 plot, where the lowest SOC content was measured, we observed an increase in $q\text{CO}_2$ and a decrease in
295 MI, highlighting that the microbial community was under stressed (Balota et al., 2004; Braman et al.,
296 2016; Laudicina et al., 2011) and less efficient conditions (Masciandaro et al., 1988; Saviozzi et al., 2001).
297 Therefore, it is likely that the mineral fertilizer application in Conv management promoted the microbial

298 activity, but with a low usage efficiency of C compounds, thus impacting the SOC pool (Braman et al.,
299 2016). The organic management exhibited lower qCO_2 and higher MI; similar results were obtained by
300 Fließbach et al. (2007) who observed lower qCO_2 in organically managed soils, and Saviozzi et al. (2001)
301 who found higher MI values in forest and grassland soils than in arable fields. Thus, organic management
302 could have resulted in soil conditions that favor microbial activity, which have better energy (i.e., carbon)
303 efficiency, thereby favoring SOC accumulation (Fließbach et al., 2007; Saviozzi et al., 2001).

304 On the other hand, both the organic and mineral fertilizers applied in Org1 and Conv-managed plots,
305 respectively, led to an increase in the available pools of C and N. This increase would lead to the
306 supposition that similar hydrolytic enzyme activities linked to C and N cycles (β -glu, α -glu, NAG, β -xyl,
307 and β -cel) would be observed in Org1 and Conv. It is noteworthy that both organic management (with
308 compost application) and N fertilization could increase the enzyme activities involved in C and N cycles
309 (Bowles et al., 2014; García-Ruiz et al., 2008; Stursova and Sinsabaugh, 2008). However, only Org1
310 resulted in higher enzymatic activities, probably owing to the input of organic fertilizers (Baldi et al., 2018;
311 García-Ruiz et al., 2008; Marinari et al., 2006). Nevertheless, the lower MBC in Conv makes the
312 comparison of the enzymatic activities difficult, as their changes could be due to both the management
313 and/or the MBC content. For this reason, it is more appropriate to consider the specific enzyme activities
314 (Gil-Sotres et al., 2005; Mazzon et al., 2018) which gives the enzymatic activity per unit of MBC, thus
315 highlighting the differences owing to management strategies. Indeed, the specific hydrolytic enzyme
316 activities involved in C and N cycles (β -glu, α -glu, NAG, and β -xyl) showed similar values (generally
317 higher than those measured under the Org2 management) in Conv and Org1, confirming that both
318 mineral N fertilization and compost addition induced the production/activation of those activities.

319 Similar to the specific hydrolytic enzyme activities, also Lac and Dehy oxidative specific activities showed
320 no differences between Conv and Org1 managements and only Tyr specific activity resulted significantly
321 higher in the Conv-managed plots. Soil oxidative enzyme activities determination is really important as
322 these enzymes play a crucial role in soil nutrient cycles as they can oxidize phenolic compounds and
323 degrade humic substances with the release of C and nutrients (Piotrowska-Długosz, 2014; Sinsabaugh,

324 2010) (Piotrowska-Długosz, 2014; Sinsabaugh, 2010). The increased Tyr activity with Conv management
325 indicates the need for the microbial biomass to recover nutrients (C and N) from the stabilized organic
326 matter. Both the hydrolytic enzymes activities (β -glu, α -glu, NAG, β -xyl, and β -cel) and Tyr activity were
327 positively correlated with the $q\text{CO}_2$ (Table 4), emphasizing the strong linkage between enzyme activities
328 and microbial metabolic efficiency. These two simple soil quality indexes represented two key points of
329 the same soil biochemical process, linking the recovery and the efficient use of nutrients and indicating
330 that in the Conv-managed plots the microbial community was less efficient and mainly focused on the
331 activation of the oxidative enzymes. Thus, if the individual utility of the simple soil quality indexes as soil
332 quality indicators is considered weak (Gil-Sotres et al., 2005), a combined evaluation can strengthen their
333 significance in terms of biochemical processes and soil quality assessment.

334 The available P content and the PME_{MBC} activity did not show significant differences between Conv and
335 Org1 management, suggesting that the management did not impact the P cycle. This finds support on
336 the C:P_{enz} and on the N:P_{enz} ecosystem ratios which showed comparable values with Conv and Org1,
337 indicating that the hydrolytic activity was not preferentially focused on the acquisition of P compared to
338 C or N (Giacometti et al., 2021; Sinsabaugh et al., 2008). Together, the simple and complex indexes
339 delineate a consistent picture. Conv and Org1 were similar in terms of acquisition activity (specific
340 enzyme activities and ecosystem ratios), indicating that both organic and mineral fertilizers, in this
341 context, were able to supply C, N, and P equally to agroecosystems. However, they differ in terms of
342 microbial metabolic response with the metabolic quotient ($q\text{CO}_2$) and index (MI) that showed a positive
343 metabolic response and a higher soil quality with Org1. This becomes evident with the SQI which
344 showed lower values with the Conv management, indicating that it led to a lower overall soil quality
345 Additionally, also the PCA clearly distinguished the Conv management from the organic management.

346

347 **The organic agroecological management (Org2)**

348 As previously observed comparing Conv and Org1 managements, SOC content resulted to be higher
349 also in Org2 with respect to Conv, and significant differences were observed also between Org1 and

350 Org2 (Conv < Org2 < Org1). The differences observed between the two organic managements could be
351 linked to the input of C into the soil; indeed, while Org1 management involves the addition of organic
352 fertilizers, Org2 relies purely on the intercropping system (sampled here with faba bean) and, as
353 previously observed in other studies (Giacometti et al., 2014; Plaza et al., 2012), while manure could
354 increase SOC content by 35–50%, crop residues increased it only by 10–19%. We already stated that
355 probably the mineral fertilizer application in Conv management promoted microbial activity, but with a
356 low C use efficiency (high qCO_2 and low MI), thus impacting on the SOC content (Braman et al., 2016).
357 Similar to Org1, also the Org2 showed lower qCO_2 and higher MI, indicating that also organic
358 agroecological management could enhance soil conditions that favor both microbial activity and SOC
359 accumulation (Fließbach et al., 2007; Saviozzi et al., 2001). Therefore, both Org1 and Org2 induced
360 favorable conditions for microbial biomass, confirming that the adoption of organic management,
361 independently from the strategy chosen, could effectively have positive effects on this component (Baldi
362 et al., 2018; Lemanceau et al., 2014; Plaza et al., 2012).

363 On the other hand, the Org2 management led to lower soil DOC and TDN content than those in the
364 Org1-managed plots. Hence, while organic fertilization could contribute to available C and N content to
365 the same extent as mineral fertilization, intercropping and crop residues incorporation not. However, the
366 hydrolytic enzyme activities involved in C and N cycles (β -glu, α -glu, NAG, β -xyl, and β -cel) resulted to
367 be lower in Org2 than in Org1 and Conv, and these differences increased considering the specific enzyme
368 activities since the MBC in the Org2 was higher than that in Conv and Org1. Therefore, the lower C and
369 N availability (i.e. presence of less quantity of substrate that could be directly mineralized or immobilize)
370 reduced the hydrolytic enzyme activity probably favoring other activities (i.e. the oxidative enzyme
371 activities).

372 Among the oxidative enzyme activities, Dehy and Lac activities were higher in Org2, while Tyr activity
373 was higher in Conv. The increased Lac activity in Org2 could be the microbial response to the low TDN
374 content measured in these soil samples because, as suggested by Sinsabaugh (2010), N availability is one
375 of the main factors controlling soil phenol oxidase activity, such as Lac (Fig. 5). Indeed, the soil

376 DOC:TDN ratio was higher in Org2, supporting the previous explanation for the increased Lac activity
377 (Fig. 5). Similarly, the $C:N_{enz}$ ecosystem ratio was higher in Org2, indicating the requirement of higher
378 hydrolytic enzyme activity to recover C than N (Giacometti et al., 2021; Sinsabaugh et al., 2008). The two
379 C:N ratios (soil and enzymatic) appear to be contradictory, as the first (DOC:TDN) suggests a greater
380 requirement to recover N than C, while the second ($C:N_{enz}$) showed a higher activity related to C
381 acquisition. The link between these two contrasting results could be explained by the increased Lac
382 activity (Fig. 5). While the increase in Lac activity was due to the reduced TDN content in Org2, there
383 was a positive correlation between Lac activity and the $C:N_{enz}$ (Table 4), suggesting a link between these
384 two parameters. Thus, it could be assumed that the low TDN content in Org2 induced Lac activity, which
385 initiated the degradation of faba bean residues and proceeded through the hydrolytic enzyme activities
386 involved in the C cycle (Moorhead and Sinsabaugh, 2006; Sinsabaugh and Shah, 2011), leading to a higher
387 $C:N_{enz}$ ratio (Fig. 5). Therefore, the two contrasting parameters were, in fact, the result of the same
388 biochemical process.

389 The available P content did not show significant differences among the three management strategies, and
390 the same was observed for the PME_{MBC} . This suggests that neither Conv nor Org managements did not
391 significantly impact the P cycle, and that probably they covered the crop and soil microbial biomass P
392 requirements. Nonetheless, the $C:P_{enz}$ and the $N:P_{enz}$ ecosystem ratios showed that the enzymatic activities
393 were mainly focused on P acquisition activity than C and N recovery only in Org2 (Giacometti et al.,
394 2021; Sinsabaugh et al., 2008), thus indicating a stoichiometric P imbalance only in Org2.

395 Therefore, the acquisition activity in Org2 was influenced by the insufficient N (higher DOC:TDN) and
396 P (lower $C:P_{enz}$ and $N:P_{enz}$) availabilities. However, the metabolic quotient (qCO_2) and index (MI), and
397 the SQI showed a positive metabolic response and a higher soil quality not only with Org1 but also with
398 Org2. This indicates that even if theoretical deficiencies or imbalances in terms of C:N:P were identified
399 in Org2, the microbial activity was efficient and functioned not only to fill these imbalances but also to
400 maintain adequate soil quality without affecting the SOC. Indeed, it is noteworthy that SOC content is
401 somehow “the core” of the biochemical soil quality indicators, and in this study, SOC and calculated

402 indexes (simple and complex) seem to indicate the same outcome: both the organic managements were
403 able to maintain the soil quality despite the differences in biochemical processes. Additionally, PCA
404 clearly distinguished the Conv management from both the two organic managements, corroborating that
405 different approaches to organic management bring equal benefits in terms of soil quality compared to a
406 conventional agronomic approach.

407

408 **Conclusions**

409 All tested managements affected the soil quality, although the two organic managements, independent of
410 the approach, improved the soil quality compared to the conventional management. Both organic
411 management strategies induced higher MBC, SOC, and TN content, and increased activities of PME,
412 Dehy and Lac. Simple and complex indexes indicated that Org1 and Org2 promoted higher MI, C:N_{enz},
413 and SQI. However, Org1 and Org2 differed in terms of soil processes, as shown by C:P_{enz}, N:P_{enz},
414 DOC:TDN, and Lac activity.

415 This study lays the foundations for the simultaneous use of multiple SQIs in order to consider both the
416 final outputs and the processes that determine them. In fact, the SQIs considered here were able to
417 discriminate not only Conv and Org management strategies but also the two different organic
418 management strategies (Org1 and Org2). Further research comparing different organic management
419 approaches is needed to identify the most appropriate sustainable management and to implement the use
420 of SQIs at the local level in generating a parameter dataset for different soils and crops.

421

422 **CRedit authorship contribution statement**

423 Mazzon: investigation, formal analysis, writing, review and editing

424 Cavani: formal analysis, writing, review and editing

425 Ciavatta: supervision, review and editing

426 Campanelli: conceptualization, methodology

427 Burgio: supervision, funding acquisition

428 Marzadori: supervision, funding acquisition

429

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432

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