

1 **Agro-environmental aspects of conservation agriculture compared to conventional systems: a**
2 **3-year experience on 20 farms in the Po valley (Northern Italy)**

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24 crop

25 **Abstract**

26 An evaluation of the effect of the conservation agriculture (CA) on agro-environmental aspects is
27 needed at the farm scale in intensive production systems, which are likely prone to reduce soil
28 fertility. Here, as part of the HelpSoil LIFE+ Project and involving 20 farms in the Po valley
29 (Northern Italy), we have estimated the soil organic carbon (SOC) content, SOC stock, crop yield,
30 biological fertility, soil biodiversity, and economic efficiency under different agricultural systems
31 (CA and conventional, CvtA) at the beginning (March 2014) and end (October 2016) of the
32 experimental period. CA was mostly represented by no-till practice (NT) coupled with the
33 cultivation of winter cover crops. Minimum tillage (MT) was considered as CA or CvtA practice
34 according to the farm design. The CA practices have been implemented on the monitored farms at
35 different times (Long-term=before 2006, Medium-term=between 2006 and 2013, Short-term=after
36 2013). A direct comparison between CA and CvtA of soil-related variables, yields, and costs was
37 performed on 14 out of the 20 farms; data were statistically treated with a linear mixed model.
38 Overall, CA resulted in significantly higher SOC content, SOC stock, biological fertility, QBS-ar,
39 and earthworms for the Medium-term group. Considering the effect of tillage practices observed on
40 the 20 farms, SOC content was the highest in NT for the Long-term group. The biological fertility
41 index was higher in NT and MT compared to CvtA within the Long-term and Medium-term groups
42 in 2016. QBS-ar was the higher in MT and NT than CvtA for the Long-term and Medium-Term
43 groups. The number of earthworms was the highest under NT for the Long-term group. Maize,
44 winter wheat, and soybeans yields were generally 1 t ha⁻¹ higher in CvtA than in CA, but this did
45 not reach statistical significance. The cost for herbicides was 18% more expensive in NT, whereas
46 the fuel consumption and total costs for weeding operations did not differ between NT and CvtA.
47 The overall outcome of the analysis was that CA is a viable solution for intensive farms in the
48 monitored area, but further skills need still to be acquired in to enhance its economic feasibility.

50 **Highlights**

- 51 • Conservation and conventional agriculture (CA, CvtA) evaluation on 20 farms in 3 years
- 52 • Implementation_Year (IY) of CA differed among the farms
- 53 • SOC and biological fertility index were higher in CA than in CvtA according to IY
- 54 • CA of recent IY was found in higher SOC storage and lower yield than CvtA
- 55 • CA may be more profitable than CvtA if cover crop and weed management improves

56

57 **1. Introduction**

58 Agriculture is required to face major agro-environmental threats, such as the increasing carbon
59 dioxide (CO₂) concentration in the atmosphere, decreasing biodiversity, and limited water
60 availability (Bouma and McBratney, 2013); these processes can be effectively mitigated by an
61 adequate management of the soil (McBratney et al., 2014). Conservation agriculture (CA),
62 originally aimed at reducing water and wind erosion in the United States (Faulkner, 1943), was
63 recently promoted by the Common Agricultural Policy of the European Union (CAP, Rural
64 Development Programme 2014 -2020; Basch et al., 2011) to tackle the above mentioned agro-
65 environmental issues (Armengot et al., 2016). CA consists in a set of agronomic practices, which
66 includes: (1) minimal soil disturbance, performed through several techniques, i.e. minimum tillage
67 (MT) and no-till (NT); (2) permanent soil cover that is ensured by retaining crop residues and (3)
68 adopting crop rotations that include cover crops (Palm et al., 2014). Integrated nutrient management
69 was indicated by Lal (2015) as another conceptual principle of the CA systems, obtained by nutrient
70 recycling, biological nitrogen fixation, and cautious use of chemical fertilizers, contributing to a
71 sustainable production system.

72 Diverse reviews dealing with the evaluation of the benefits determined by the switch from
73 conventional agriculture (CvtA) to CA in temperate regions have been published in the last decade;

74 contrasting results are shown in these reviews, suggesting that such a conversion does not always
75 result in environmental and economic benefit (Table 1). The data reported by Virto et al. (2012),
76 Abdalla et al. (2013), and Stavi et al. (2016) show that the contribution of CA practices, namely NT,
77 on carbon sequestration is higher than under CvtA. Conversely, Ogle et al. (2012) stated that SOC
78 sequestration is even lower under reduced tillage than in CvtA, while other authors reported no
79 difference between the two systems (Aguilera et al., 2013; Palm et al., 2014; Ranaivoson et al.,
80 2017). According to Powlson et al. (2014), the apparent increase in soil organic carbon (SOC) under
81 NT when compared to CvtA is mostly due to the redistribution of C in the topsoil and does not
82 necessarily lead to a net increase in SOC stock. Moreover, time after CA implementation is a factor
83 affecting SOC increase (Pittelkow et al., 2015). Evidences from a study conducted by Virto et al.
84 (2012) suggest that the variability in SOC storage induced by the conversion to NT, seems mostly
85 due to the crop production variability as crop C input differences was the only factor significantly
86 explaining (about 30% of the total variability) the SOC stock increase in NT compared to CvtA.
87 Ogle et al. (2012) analyzed 74 published studies carried out in the United States and found that the
88 adoption of NT in conventionally managed croplands might reduce SOC stocks. On the contrary the
89 role of cover crops combined with NT in increasing SOC storage has been reported by many
90 authors (Aguilera et al., 2013; Palm et al., 2014; Lal et al., 2015).

91 Evidence of a reduction of greenhouse gases emissions by CA has been reported by many authors
92 (Morris et al., 2010; Corsi et al., 2012; Perego et al., 2016). Concerning the nitrous oxide, (N₂O)
93 which is acknowledged as one of most potent gas in terms of warming potential, it was highlighted
94 that CA has a similar or negative effect on N₂O emissions relative to CvtA (Abdalla et al., 2013;
95 Palm et al., 2013; Powlson et al., 2014). Available data suggest that the switch from CA to CvtA
96 practices is likely to enhance soil biodiversity (Knowler and Bradshaw, 2007; Powlson et al., 2014).
97 In particular, Van Capelle et al., (2012), in a review focused on German data, found that, although
98 microorganisms generally benefit from a reduction of tillage intensity, tillage effects on soil

99 organisms vary according to soil texture, and therefore tillage system should be chosen on the basis
100 of the local soil characteristics.

101 Positive effects on soil structure were reported by several authors in recent reviews (Hobbs et al.,
102 2008; Morris et al., 2010; Abdalla et al., 2013; Powlson et al., 2014). It was acknowledged that
103 progressive formation of macropores might compensate the soil compaction occurring in the first
104 phase of NT implementation due to roots and faunal activity with time (Kay and Vann, 2016).
105 Moreover, the residue retention on the soil surface creates optimal conditions for macrofauna
106 (Mutema et al., 2013) and particularly for earthworms (Briones and Schmidt, 2017), which in turn
107 promote the development of soil structure. Moreover, soil structural and hydraulic properties benefit
108 from the cover crops cultivation (Blanco-Canqui et al., 2015).

109 Various aspects concerning farm management are regarded as critical in the adoption of the CA
110 practices; both positive and negative effects have been listed in reviews published in the last decade
111 (Table 1). Hobbs et al. (2008) and Scopel et al. (2013) stated that farm labor is saved by reducing
112 tillage operations and the associated fuel consumption. Conversely, Powlson et al. (2014) reported
113 that suitable machinery for planting under conservation tillage might not be available, especially for
114 small farmers in less developed countries; in addition extra labor or use of herbicides for weed
115 control might imply increasing costs. Many authors acknowledged the negative effect of CA on
116 weed control in other reviews (Knowler and Bradshaw, 2007; Stavi et al. 2016; Ranaivoson et al.,
117 2017). In the calculation of the economic balance, a critical variable is the revenue generated by
118 yield, which is generally lower under CA than CvtA (Ogle et al., 2012; Powlson et al., 2014;
119 Pittelkow et al., 2015), but might be similar (Knowler and Bradshaw, 2007; Hobbs et al., 2008;
120 Stavi et al. 2016; Ranaivoson et al., 2017) or slightly higher (Farooq et al., 2011) due to the crop
121 residues retention. Blanco-Canqui et al. (2015) reported that cover crop cultivation under CA often
122 results in yields that do not differ from those under CvtA.

123 The overall outcome of the examined reviews and papers is that it is required to define farm-
124 specific options to boost the potential of CA and to reduce environmental and economic drawbacks.

125 Recently, multiple studies have addressed CA in tropical, sub-tropical, and arid regions, with a
126 focus on smallholder farmers (Giller et al., 2015; Brown et al. 2107a, Brown et al., 2017b, Farris et
127 al., 2017). However, the implementation of CA in Europe (Soane et al., 2012), and in particular in
128 Italy, is still an ongoing process whose environmental and economic feasibility needs to be
129 evaluated. In Italy, CA is currently supported by the EU's CAP and the rural development
130 programmes of the Italian administrative regions, such as the five regions laying in the Po valley
131 (Piedmont, Lombardy, Emilia-Romagna) and Veneto and Friuli Venezia Giulia plain (Northern
132 Italy). For simplicity, hereafter in the text, the entire flat area is referred to as Po valley. In this area,
133 the organic carbon stock stored in the topsoil (i.e. 0.3 m depth) is 34 to 60 Mg ha⁻¹ and the potential
134 for further uptake is estimated to be at least 12.8 Mg ha⁻¹ of CO₂ equivalent if soils are managed
135 appropriately (Brenna et al., 2014). The Europe Commission funded the HelpSoil project (LIFE12
136 ENV/IT/000578), which was carried out on 20 farms in the Po valley and aimed at: i) strengthening
137 the ecological functions of the soils (e.g. carbon sequestration, increase of fertility and edaphic
138 biodiversity, protection against erosion); ii) evaluating the opportunity of coupling subsurface drill
139 irrigation and no-till to enhance water use efficiency; iii) improving the nitrogen use efficiency
140 while testing various fertilization techniques, in particular in the usage of livestock slurry; and iv)
141 reducing the use of pesticides for the control of plant pests and diseases. The present study was set
142 within the framework of the HelpSoil Project, under the assumption that only the on-site assessment
143 of environmental and economic variables enables a sustainable adoption of CA practices. The study
144 has the objective of evaluating the agro-environmental aspects (i.e., soil C-related variables,
145 biological fertility, edaphic biodiversity, crop yield, and economic efficiency) in a direct
146 comparison between CA and CvtA systems on working farms where CA practices have been
147 implemented at different times.

148 **2. Materials and methods**

149 **2.1. Study site and experimental design**

150 Twenty farms were chosen within the Po valley in 2013 with the first aim of evenly representing the
151 pedoclimatic conditions and cropping systems occurring in the area addressed by the HelpSoil
152 project (Figure 1). The Po valley is a flat area and is approximately 47000 km² wide; this area is
153 characterized by peculiar traits that make it unique for a variety of meteorological and agricultural
154 production systems variables (Fumagalli et al., 2013; Acutis et al., 2014). Climate is mild, the mid-
155 latitude version of the Humid subtropical climate (Köppen climate classification Cfa and Cfb), and
156 farming systems are generally intensive with high N input (Perego et al., 2013). The farms
157 designated for the present study were characterized by different production systems, a broad range
158 of soil properties, and critical issues to be addressed (e.g. low SOC content, weed pressure). Thus,
159 the majority of the Agricultural_Systems under comparison were NT and CvtA, except for
160 Cavallini, Rebollini, Euroagricola and Zanone farms (where only NT is present), Arisi (NT vs MT
161 vs CvtA), Carpaneta and Grandi farms (NT vs MT), Don Bosco and Cerutti (MT vs CvtA). Such an
162 experimental set up allows analyzing agro-environmental aspects under a wide range of technical
163 and pedological conditions.

164 Over the course of the experiment, a varied range of meteorological conditions was recorded on the
165 20 farms involved in the project (Supplemental File 1); this aspect, along with the different
166 pedological characteristics, allowed us to capture a wide variety of conditions in which both CA and
167 CvtA practices were adopted. Mean annual rainfall from 2014 to 2016 varied from 709 mm
168 (RuoZZi) to 1645 mm (La Fattoria, Zanone). The 20 locations also differed in mean annual
169 temperature, which was the highest at Rossi (15.4 °C) and the lowest at Gli Ulivi (13.5 °C in 2016).
170 The monitoring on the demonstration farms was carried out from late 2013 to October 2016 (i.e. 32
171 months). The demonstration fields were set up on each farm with two or three replicates to compare
172 production and environment-related aspects under the farm current condition (i.e. CvtA, MT or NT)
173 and the CA alternative option (MT or NT). The farms' key features, such as site location, soil
174 texture class, CA implementation year, crop rotation, and tillage treatments are listed in Table 2.
175 Further details on cover crops cultivation and soil characteristics are given in Supplemental File 2.

176 The chemical and physical parameters of soils were measured on soil sampled in early 2014.
177 Texture classes varied from sandy loam to clay; silty loam and silty clay loam were the soil types
178 most represented in the present study. A different code was assigned to the farms where CA was
179 implemented before 2006 (Long-term), from 2007 and 2013 (Medium-term), and at the beginning
180 of the experiment in 2013 (Short-term); this temporal distinction was chosen following the findings
181 of Pittelkow et al. (2015). Machinery with varied characteristics and brands were adopted for tillage
182 and sowing, according to the on-farm availability and the tested tillage treatments. In an attempt to
183 picture real farm conditions, dates of tillage, sowing, harvesting, weed and pest control, and
184 irrigation were defined by local pedoclimatic conditions and farmers' experience.
185 Complete information about the 20 farms is given at the official project website
186 <http://www.lifehelpsoil.eu/en/demonstrative-farms/>.

187 **2.2. Data collection**

188 The collection of soil, crop, and field operation-related data was aimed at evaluating soil
189 functionality along with the economic and technical feasibility of the tested treatments on the
190 demonstrative farms. The following variables were measured at the beginning (March 2014) and at
191 the end of the experiment (October 2016): SOC concentration and stock, soil bulk density, soil
192 microbial carbon and respiration, the biological fertility index - BFI (Francaviglia et al., 2017),
193 microarthropods, and the number of earthworms.

194 Prior to the data collection in 2014, soils were sampled in each experimental field to determine soil
195 texture, pH (in H₂O and KCl) cation exchange capacity, magnesium, calcium, and carbonate (total
196 and active) content.

197 Soil samples (three independent replicates in each experimental field; 131 samples collected both in
198 2014 and in 2016) were collected at 0-0.3 m depth in each experimental field. The SOC content (g
199 kg⁻¹) was determined both on air-dry subsamples of 40-mg weight (0.5 mm sieved) using a
200 ThermoQuest NA1500 elemental analyzer (Carlo Erba, Milano, Italy) and with the Springer-Klee

201 method (TOC) via oxidation with $K_2Cr_2O_7$ and subsequent titration of unreduced $Cr_2O_7^{2-}$ with
202 $Fe(NH_4)_2(SO_4)_2$. The value measured by the former method was subtracted from the C-carbonate
203 content, which was previously measured using a calcimeter. The latter method was employed as it
204 is required for the estimation of the biological fertility index. In the present text, SOC content refers
205 to the value estimated by the elemental analyzer.

206 The SOC stock was calculated from the SOC relative content and the bulk density measured on the
207 same soil plot (three replicates at two soil depths, 0-0.15 m and 0.15-0.3 m in each experimental
208 field; 262 samples collected both in 2014 and in 2016). The SOC stock (Mg) was estimated in the
209 0.3 m topsoil by using the formula [1] reported by Batjes et al. (1996):

$$210 \text{ SOC stock} = \text{SOC} \times \text{topsoil depth} \times \text{BD} \times (\text{RF}) \times 10000 \text{ m}^2 \quad [1]$$

211 where SOC (%) is the organic carbon content (%), *topsoil depth* is 0.3 m, BD is the topsoil bulk
212 density ($Mg \text{ m}^{-3}$), and *RF* is the rock fragment content (%). BD was estimated on a known volume
213 soil sample, which was collected with a cylindrical metal sampler pressed into the soil to both 0.15
214 and 0.3 m depths (three replicates). The sample was oven-dried at 105°C and then weighed; the
215 value of bulk density was calculated as the ratio of oven-dried mass over the soil sample volume (g
216 cm^{-3}).

217 In an attempt to quantify the contribution of CA in SOC content and SOC stock, the data observed
218 in CA in 2016 was related to those in CvTA for each implementation group, by applying a formula
219 used by Powlson et al. (2014):

$$220 \text{ SOCratio} = (\text{SOC}_{\text{CvTA}} - \text{SOC}_{\text{CA}}) \times \text{SOC}_{\text{CvTA}}^{-1} \quad [2]$$

$$221 \text{ STOCKratio} = (\text{STOCK}_{\text{CvTA}} - \text{STOCK}_{\text{CA}}) \times \text{STOCK}_{\text{CvTA}}^{-1}$$

222 These indices were multiplied by -1 so that the positive contribution of CA on SOC storage was
223 indicated by a positive value.

224 Microbial biomass carbon (MBC, $\mu\text{g g}^{-1}$ dry soil) was estimated via fumigation extraction,
225 following the procedure detailed by Francaviglia et al. (2017). The cumulative microbial respiration
226 was determined over 28 days of incubation by measuring the CO_2 emitted from a 20-g moist sample

227 after 1, 3, 7, 10, 14, and 21 days. The cumulated CO₂ emitted from 21 to 28 days of incubation
228 represented the basal respiration value. The following parameters and indices, which were derived
229 from TOC and microbial-related measurements, were taken into account to calculate the BFI:
230 organic matter OM (TOC × 1.72), MBC (μg g⁻¹ dry soil), cumulative respiration (mg CO₂-C h⁻¹ kg⁻¹
231 soil), basal respiration (mg CO₂-C h⁻¹ kg⁻¹ soil). The metabolic and mineralization quotients were
232 calculated as follows:

$$233 \text{ metabolic quotient} = \text{basal respiration} \times \text{MBC}^{-1} \times 10^3 \text{ (}\mu\text{g h}^{-1} \mu\text{g}^{-1}\text{)} \quad [3]$$

$$234 \text{ mineralization quotient} = \text{cumulative respiration} \times \text{TOC}^{-1} \text{ (}\mu\text{g } \mu\text{g}^{-1}\text{)} \quad [4]$$

235 For each of these parameters and indices, a score (1 to 5) was assigned; score ranges related to each
236 parameter were derived from Francaviglia et al. (2017) and are given in Table 3. The BFI was
237 calculated by adding up the scores obtained for the five microbial indices.

238 As for the microarthropods, the procedure was carried out by applying the method reported by
239 Tabaglio et al. (2009a). Accordingly, an undisturbed soil core (10 cm × 10 cm × cm) was sampled;
240 microarthropods were extracted from each core using a Berlese-Tullgren funnel and then stored in a
241 storage solution (i.e. 70% industrial ethylic alcohol and 5% glycerol). The microarthropods were
242 counted using a microscope and soil biological quality was expressed using the QBS-ar index
243 (Parisi et al., 2005). The QBS-ar index is based on the assumption that the richer is the well-adapted
244 microarthropod community, the higher the soil quality. The degree of soil adaptation of each
245 microarthropod group is defined by assigning an eco-morphological score (EMS), ranging from 1 to
246 20, according to the morphological traits that are suitable for the edaphic habitat (e.g.,
247 anophthalmia, depigmentation, and reduction of appendices). The QBS-ar is the numerical value
248 (generally between 20 and 280) resulting from the sum of the EMS indexes assigned to each
249 taxonomic group of microarthropods.

250 The number of earthworms was counted on 15625 cm³ (25 cm × 25 cm × 25 cm) undisturbed soil
251 samples (FAO, 2008).

252 Also, for both the tested treatments on each farm, the aboveground biomass and crops grain yield
253 were estimated by weighing the plants harvested on three areas of 5 m² in each experimental field
254 and then pooled together. The biomass and grain dry matter content were obtained by weighing a 1-
255 kg biomass subsample after 24 h at 105°C in a dry oven.

256 An index proposed by West et al. (2010), namely the tradeoff index, was calculated here to relate
257 the SOC difference between CvtA to CA to the difference in C-biomass yield between CvtA to CA
258 (C-yield_{CA} and C-yield_{CvtA}), which was observed over the experiment on each farm. The tradeoff
259 index was calculated as follows:

$$260 \text{ Tradeoff index} = (SOC_{CA} - SOC_{CvtA}) \times (C\text{-yield}_{CA} - C\text{-yield}_{CvtA})^{-1} \quad [5]$$

261 Where SOC_{CA} and SOC_{CvtA} are SOC content under CA and CvtA, respectively. The index was
262 calculated for 16 farms as in four farms (i.e., Cavallini, Euroagricola, Rebollini, and Zanone) NT
263 was the only examined treatment.

264 Fuel consumption and human labor were taken into account in the calculation of a simplified energy
265 and economic balance, which was performed by following the approach proposed by Grisso et al.
266 (2004) on data collected in the farms. Five farms were chosen out of the 20 farms involved in the
267 experiment to compare the effect of CA and CvtA treatments.

268 Fuel consumption (l ha⁻¹) required in field operations (i.e., soil tillage, seeding, weed control,
269 fertilization, irrigation, and harvesting) was estimated based on the number of operations, the tractor
270 power, and the time required per operation (h ha⁻¹). The calculation was performed as follows:

$$271 Q = (0.22 \times X + 0.096) \times (1 - (-0.0045 \times X \times N_{red} + 0.00877 \times N_{red})) \times P_{PTO} \times h \quad [6]$$

272 where Q = diesel fuel consumption, (l ha⁻¹), N_{red} = the percentage of reduced engine speed for a
273 partial load from full throttle (%), X = the ratio of equivalent PTO power to rated PTO power, P_{pto} =
274 the rated PTO power, kW, and h = operation time (h ha⁻¹). Values were derived from machinery
275 technical data sheets.

276 The analysis also took into account the information given by the five farmers about the material
277 purchased for crop growing (e.g., seeds, mineral fertilizers, and agrochemicals) and the labor hours
278 required for each operation; details are reported in Supplemental File 3.

279 The account of direct costs and gross crop yield enabled the calculation of the gross economic gain
280 (i.e., revenue from grain yield subtracted by direct costs) and the ratio of the revenue from grain
281 yield over direct costs, which is a dimensionless index that quantifies the efficiency of the tested
282 treatments.

283 **2.3. Statistical analysis**

284 Effects of Agriculture_Systems (CA vs CvtA), Implementation_Year, and Farm were tested on
285 SOC relative content, SOC stock, bulk density, MBC, microbial cumulative and basal respiration,
286 BFI, QBS-ar, and earthworms using a repeated measure mixed model with unstructured matrix
287 (IBM – SPSS 25, IBM Corporation, Armonk, New York, US). The Farm factor was nested within
288 the CA implementation year factor (Implementation_Year). The levels of the factor
289 Implementation_Year were three, namely Long-term (before 2006), Medium-term (from 2006 to
290 2013), and Short-term (after 2013). Repeated measures were used as two samplings were carried
291 out in the same field site in 2014 and in 2016. The mixed model was applied to the data collected
292 under the tested treatments on the 14 farms for which an actual comparison were set between CA
293 and CvtA (see details on treatments tested on each farm in Table 2). The Sidak post hoc test was
294 applied for means comparison.

295 The relationship between the C-related variables was tested using linear and non-linear regression
296 to study the trend in microbial respiration affected by the SOC content.

297 The linear mixed model was run by splitting the dataset by crop to investigate the effect of
298 Agriculture_Systems and Implementation_Year on the grain production of the most common crops,
299 namely maize, soybean, and winter wheat. For the other crops, less than two replicates across farms

300 were available and, in turn, the related results were assumed to be insufficient for testing the effect
301 of the Agriculture_System.

302 After checking for normality and homogeneity of variances, a one-way ANOVA was run to test the
303 effect of the factor Year on the SOC tradeoff index, which is the ratio of SOC variation from CvtA
304 to CA (NT or MT, according to the farm management) over the C-yield variation from CvtA to CA.
305 As for the simplified economic balance, a one-way ANOVA model was applied to data of oil
306 consumption for field operation, costs for raw material purchase, labor hours, total costs, the gross
307 economic gain (i.e., revenue subtracted by costs), and the ratio of revenue over costs to find
308 differences between NT and CvtA (NT vs MT in Carpaneta).

309 **3. Results**

310 In comparison with CvtA, overall positive effects of CA were found in the following farms: Arisi,
311 Cerzoo, La Fattoria, Mosca, Rossi, Ruozzi, Sant’Ilario, and Sasse Rami. No relevant differences
312 were observed in Cerutti, Don Bosco, Gli Ulivi, Pasti, and Vallevecchia; negative effects of CA
313 were not found. The results of SOC content and stock, C-microbial biomass related variables,
314 microarthropods, earthworms, yield, carbon tradeoff index, gross gain, and economic efficiency
315 index are listed below.

316 **3.1. Carbon-related variables**

317 Regarding the application of the mixed model, the between-groups effect of the Farm X
318 Agricultural_Systems was significant for SOC content (measured via both the methods applied,
319 Elemental Analyzer, and Springer-Klee), SOC stock, C-microbial biomass, cumulative respiration,
320 and the BFI (Table 4). Farms where a significantly higher SOC content (Elemental Analyzer) was
321 found in CA than in CvtA were: Arisi (17.9 and 16 g kg⁻¹, +11%), Cerzoo (15.2 and 13 g kg⁻¹,
322 +17%), Sant’Ilario (21.6 and 18.7 g kg⁻¹), and Sasse Rami (17.9 and 12.5 g kg⁻¹, +43%).
323 Conversely, CvtA was found to have slightly higher SOC content in La Fattoria (20 and 18.2 g kg⁻¹,
324 +10%). The results of the analysis performed on TOC were consistent with those of SOC content.

325 The analysis also showed a significant effect of the interaction between Agricultural_Systems and
326 Implementation_Year on SOC content and BFI. Overall, the significant differences between CA
327 and CvtA were found for the Medium-term group (Table 5). The first run of the linear mixed model
328 highlighted a non-significant effect of the sampling depth on bulk density and consequently the
329 mixed model was applied to the mean bulk density data, which were calculated as the mean
330 between the two layers for each experimental field. The CvtA resulted in significantly higher bulk
331 density than CA for the medium-term group. Farms, where BD in CvtA was higher than in CA,
332 were: Cerzoo (1.56 and 1.46 Mg m⁻³), Diana (1.37 and 1.25 Mg m⁻³), Pasti (1.25 and 1.16 Mg m⁻³),
333 Sant’Ilario (1.26 and 1.13 Mg m⁻³) and Sasse Rami (1.23 and 1.12 Mg m⁻³). Similarly to the SOC
334 content, SOC stock was significantly higher in CA than in CvtA for the Medium-term group. As for
335 the significant interaction between farms and Implementation_Year, in two Medium-term and
336 Short-term farms (i.e. Sasse Rami and Ruozzi), CA determined higher SOC stock in comparison
337 with CvtA. A positive and significant contribution of CvtA in SOC stock was not found in any
338 farm. Considering all of the collected data, including those on the farms where only CA was
339 adopted, SOC content and stock were the highest in the Long-term group (Figure 2a, 2b).

340 The SOCRatio and STOCKratio are shown in Figure 3. The displayed bars are the confidence
341 interval at 95%; bars crossing the zero point indicate that the SOC content and stock under CA does
342 not differ from the one in CvtA. In agreement with the statistical analysis results, the Medium-term
343 group had a more significant effect of CA on SOC concentration and stock than in CvtA.

344 The CvtA resulted in a lower MBC within the Medium-term group, while it was higher, even if not
345 significantly, for the Short-term group (Table 5). MBC was significantly higher in CvtA than in CA
346 only in Cerutti (299 and 193 µg g⁻¹); in Cerzoo, Diana, Pasti, Sant’Ilario, Sasse Rami, and
347 Vallevicchia, CA’s MCB was double that of CvtA’s (on average, 236 and 119 µg g⁻¹). Regarding
348 the effect of tillage, higher MCB across Implementation_year was generally observed in MT
349 (Figure 2c).

350 Basal respiration was affected significantly by Agricultural_Systems and Implementation_year
351 (Table 4). In particular, the lowest values were found in CA and for the Short-term group (5 mg
352 CO₂-C h⁻¹ kg⁻¹ soil) compared with the Long-term (6.3 mg CO₂-C h⁻¹ kg⁻¹ soil) and the Medium-
353 term (6.7 mg CO₂-C h⁻¹ kg⁻¹ soil) groups. The Agricultural_Systems × Implementation_year
354 interaction was found significant for the cumulative respiration (i.e., higher in CA × Medium-term
355 group). In two farms, the cumulative respiration was higher in CA than in CvtA (Sant’Ilario, 393
356 and 285 mg CO₂-C h⁻¹ kg⁻¹ soil; Vallevicchia: 395 and 237 mg CO₂-C h⁻¹ kg⁻¹ soil). The metabolic
357 and mineralization quotients had a trend similar to that of TOC and cumulative respiration.
358 A positive linear correlation was detected between TOC and cumulative microbial respiration data
359 collected in 2016 (Figure 4). At a SOC value higher than approximately 18 g kg⁻¹, cumulative soil
360 respiration rose steeply and in turn reduced the amount of the sequestered SOC.
361 BFI results were the highest under CA in the Medium-term group (Table 4). As for the tillage
362 practices, BFI was higher in NT and MT compared to CvtA within the Long-term and Medium-
363 term groups in 2016 (Figure 2d). Moreover, while distinguishing the evolution of the BFI by
364 classes, Agricultural_Systems and Implementation_Year (Figure 5), the most relevant improvement
365 in classes was found under NT and MT for the groups B and C, for which CvtA resulted in lower
366 classes in 2016 than in 2014.

367 **3.2. Microarthropods and earthworms**

368 Soil biodiversity was assessed by estimating the QBS-ar index of the 0.1 m topsoil and the number
369 of earthworms present in the topsoil layer (0-0.25 m) in the tested treatments of the 20 farms. The
370 highest results of QBS-ar were observed in the Medium-term group under CA, while the number of
371 earthworms generally decreased from Long to Short-term groups (Table 5). The farms where QBS-
372 ar was significantly lower in CvtA than in CA were Cerzoo (51.5 and 100.2, respectively), Pasti
373 (86.3 and 63.8, respectively), and Sasse Rami (52.3 and 12.8, respectively). Regarding tillage
374 practices, QBS-ar was generally similar between MT and NT and lower in CvtA, except for the

375 Medium-term group. The QBS-ar index was found the highest in MT for the Medium-term
376 Implementation_Year group (141); in CvtA and in NT the index was equal to 63 and 83,
377 respectively (Figure 2e).

378 CA resulted in higher earthworm abundance compared to CvtA in Cerzoo (21.2 and 2.3), Diana (27
379 and 8.3), La Fattoria (17.7 and 7.3), Pasti (30 and 5), and Ruozzi (13.7 and 7). Considering the
380 whole dataset split by tillage practices, the mean number of earthworms was the highest for the
381 Long-term group in NT (24.3) (Figure 2f). Generally, earthworms were less abundant in CvtA than
382 in NT.

383 3.3. Grain yield

384 The effect of the Agricultural_Systems was found close to the significance threshold ($p=0.07$) in
385 maize and significant in soybean ($p=0.01$) (Table 6). The grain yield of maize, winter wheat, and
386 soybean in CA and CvtA are displayed split by Implementation_Year (Long-term, Medium-term,
387 Short-term) in Figure 6. Maize yield in CvtA was 15% higher than in CA across the
388 Implementation_Year groups. Soybean grain yield was significantly lower in CA than in CvtA,
389 with a lower difference in the Long-term group (-11%) than in Medium-term (-17%) and Short-term
390 (-20%) groups. No significant difference in winter wheat yield was found between CvtA and CA.

391 The tradeoff index ($\text{Mg C-soil ha}^{-1}/\text{Mg C-crop yield ha}^{-1} \text{ y}^{-1}$) was calculated as the ratio of the SOC
392 variation over the C-biomass yield variation between NT and CvtA with the aim of simultaneously
393 considering the effect of the Agricultural_System on production and environment-related aspects.
394 The tradeoff index varied significantly between farms (Figure 7). For eight farms, the index was
395 negative as the increase in soil C stock offset the negative variation of C-yield production; these
396 farms belonged to the Medium-term and Short-term Implementation_Year groups. A decrease in
397 SOC stock and negative variation of C-yield production was estimated for five farms with no effect
398 of Implementation_Year. An increase in SOC stock and a positive variation of C-yield production
399 was calculated in the remaining four farms, which belong to the Short-term group (Arisi,

400 index=2.05), the Medium-term group (Rossi, index=1.85), and the Long-term group (Grandi,
401 index=2.57; La Fattoria, index=3.94).

402 **3.4. Costs and fuel consumption**

403 A simplified economic balance was calculated to compare the gross gain (i.e., revenue from grain
404 yield subtracted by direct costs) and the economic efficiency (i.e., the ratio of revenue over direct
405 costs) for the two treatments under comparison on five farms involved in the present study (i.e.,
406 Carpaneta, La Fattoria, Mosca, Pasti, and Ruozzi). Production costs and revenue from grain yield,
407 and in turn gross margin and economic efficiency, were different between years and farms and
408 varied according to field operation, fuel consumption, labor, and raw material purchase (e.g., seeds
409 and agrochemicals). The statistical analysis carried out to compare the costs of the operations
410 performed in both the treatments (e.g., application of slurry, sowing, and harvesting) did not show
411 any significant differences between the two Agricultural_Systems under comparison on each farm.
412 Considering the annual costs for the two Agricultural_Systems under comparison, the fuel
413 consumption was generally lower in NT than in CvtA; in Carpaneta, MT and NT did not differ
414 except in the first year when the cover crop was grown only in NT. The fuel consumption was
415 significantly higher in CvtA compared to NT in Ruozzi in the first two cropping seasons and in
416 Mosca and La Fattoria over the three years. In Carpaneta, the fuel consumption was significantly
417 higher in NT than in MT in the first cropping season and that was due to the cultivation of the crop
418 cover (i.e., crop mixture of vetch, rye, and radish), while in the third year the consumption in MT
419 was higher than in NT due to the vertical tillage machine (i.e., disc harrow). Labor hours did not
420 significantly differ between treatments.

421 Among the field operations, weeding in NT was by approximately 30% more expensive than in
422 the comparative treatment. Fuel consumption for soil tillage accounted for 40% of total
423 consumption (i.e. the 36% of total costs due to field operations) in CvtA while it was zero in NT.

424 The fuel consumption and total cost of the sod-seeding in NT (on average, 9 L ha⁻¹ and 20 € ha⁻¹)
425 did not differ to those related to the seeding in CvtA (on average, 10 L ha⁻¹ and 23 € ha⁻¹).
426 Considering the raw material purchase, the difference between NT and MT in Carpaneta in 2013-
427 2014 was mainly due to the cover crops' seeds purchase (approximately 25%). In La Fattoria the
428 winter cover crop was barley, and the seeds costs represented only 3% of the annual costs for
429 material purchase. Overall, the cost for herbicides' purchase was 18% more expensive in NT than in
430 the comparative treatment, whereas the fuel consumption and total costs for weeding operations did
431 not differ between NT and CvtA. The difference consisted in a higher number of weeding operation
432 (1 to 2), which was due to the termination of the cover crops (in Carpaneta, Pasti, and Ruozzi) and
433 to an additional intervention aimed to control a higher pressure of weeds (in Pasti and Ruozzi).
434 Crop yields, the gross margin and the indicator of economic efficiency for the treatments under
435 comparison on the five examined farms are displayed in Table 7. Variation in gross gain was
436 mainly driven by the differences in grain yield between treatments, which was generally lower in
437 NT than in the comparative treatment (-0.5 Mg DM ha⁻¹). Consequently, the gross gain was
438 generally lower in NT; conversely, the economic efficiency index was comparable and even higher
439 in NT in La Fattoria.

440 **4. Discussion**

441 *4.1 Soil-related variables*

442 In the literature, findings are reported to support the capability of CA to result in positive changes in
443 SOC content and stock compared to CvtA (Govaerts et al., 2009; Ogle et al., 2012; Virto et al.,
444 2012; Abdalla et al., 2013; Stavi et al. 2016). The statistical analysis highlighted the significant
445 effect of Implementation_Year × Agricultural_Systems on SOC storage, namely concentration and
446 stock. CA within the Long-term and Short-term groups did not result in significantly higher SOC
447 content and SOC stock (Table 5). However, this result did not inform about the gain in SOC storage
448 that is achievable in CA compared to CvtA. The data of SOCratio and STOCKratio suggest that a

449 significant SOC gain occurred for the three groups, especially for the Medium-term (Figure 3). This
450 result agreed with the data reported by Tabaglio et al. (2008; 2009a; 2009b) from four trials in the
451 Po valley. The SOCratio estimated in this study for the 0.3 m topsoil was higher than that shown by
452 Powlson et al. (2014). The low results of the SOCratio and STOCKratio of the Long-term group
453 was likely due to the low number of cases, and this is because farms where the implementation year
454 of CA is before 2006 are unlikely to allocate fields to CvtA practices. Also, in one farm belonging to
455 the Long-term group (i.e. Pasti), tillage in CvtA consisted of moderate plowing, as confirmed by the
456 low field operation costs (Table 7). Nonetheless, considering data collected under NT, also on farms
457 where CvtA practices were not performed, the long-term contribution of NT on SOC content and
458 stock is evident (Figure 2a and 2b).

459 In the present study, the BFI index was calculated to assess the effect of the agricultural systems on
460 soil biological fertility. The calculation of the BFI enabled the evaluation of the overall biological
461 status of the examined soils (Renzi et al., 2017), as it is effectively used as a multi-domain indicator
462 of biological fertility. NT and MT soils within the Long-term and Short-term Implementation_Year
463 groups scored the highest value, which was similar to the values found by Francaviglia et al. (2017)
464 for cork oak forest (16-20). The values observed in CvtA approached the range found in pastures
465 (11-13) by Francaviglia et al. (2017). Moreover, the most evident improvement in the BFI ranking,
466 namely from average to the high class, was observed in the Medium-term and Short-term
467 Implementation_Year groups.

468 The QBS-ar index is based on the assumption that the richer is the well-adapted microarthropod
469 community, the higher the soil quality, the QBS-ar was 18% lower in CvtA than in NT. Average
470 values were in agreement with the value found by Menta et al. (2018) for agricultural soils.
471 Tabaglio et al. (2009) reported higher values of QBS-ar in no-till soils compared to conventional
472 tillage soils. In this study, The QBS-ar value was the highest in CA, especially under MT, within
473 the Medium-term Implementation_Year group. The time of implementation of a certain
474 Agricultural_System might result in a difference in QBS-ar; Simoni et al. (2013) found higher

475 QBS-ar values in a recent organic maize-based agroecosystem (6 years) than in an old one (16
476 years). Similarly, we found the highest QBS-ar value for the Medium-term Implementation_Year
477 group (2007-2013) for all the Agricultural_Systems. A significant effect of the type of
478 Agricultural_Systems was also observed on the number of earthworms for the Long-term and the
479 Medium-term groups. This outcome is in agreement with Triplett and Dick (2008) who found and
480 abundance of earthworms on fields having long implemented CA practices. In CA, the abundant
481 surface mulch, which is due to cover crops and reduced tillage, provides food, nutrients and energy
482 for earthworms, arthropods, and micro-organisms below ground that also biologically till soils
483 (Hobbs et al., 2008; Ranaivoson et al., 2017). Van Cappelle et al. (2012) found that the CA
484 practises resulted in significantly higher earthworm abundance than CvtA in silty and loamy soils.
485 This result agrees with the results of the present study, in which the farms where a significant effect
486 of CA on the earthworm abundance was detected had sandy clay loam to clay soils.

487 *4.2 Crop yield and tradeoff index*

488 The general decrease in crop yield passing from CvtA to CA indicated by various authors (Ogle et
489 al. 2012; Scopel et al., 2013; Powlson et al., 2014) was particularly evident only for the Short-term
490 group. Conversely, the lower variation in C-biomass from CvtA to CA production was observed in
491 farms of the Long-term and Medium-term groups, especially in winter wheat. Van den Putte et al.
492 (2010) suggested lessening the decrease in winter cereal yield under NT by adopting a multi-crop
493 rotation, as it is a fundamental principle of the CA to make it a viable solution for farmers. This
494 practice was adopted on the farms investigated in this study. This evidence also arose from the
495 meta-analysis performed by Pittelkow et al. (2015), in which decreases in crop yield passing from
496 CvtA to NT do not occur only in the case of residues retained on soil and multi-crop rotations. An
497 outcome of this study was that the dispersion of the data set was higher in CA than in CvtA as it
498 was less stable across locations. This fact was likely due to the effect of the pedoclimatic conditions
499 and the different skills of the farmers.

500 The tradeoff index proposed by West et al. (2010) was defined under the assumption that CA
501 always results in yield decrease and SOC gain. The outcome of the present study was
502 heterogeneous, as CA did not regularly result in higher SOC stock and concurrent yield losses.
503 Results of farms where the CA was implemented as of 2006 (i.e. Medium-term and Short-term
504 groups) indicated that the SOC stock variation from CA to CvtA was positive, while yields
505 decreased. The Long-term group resulted in null to positive results. In the other two farms of the
506 Long-term group (i.e., Grandi and La Fattoria), positive values indicated a higher SOC stock
507 variation in CA than in CvtA and concurrent higher yields.

508 *4.3 Costs and energy balance*

509 Overall, the gross gain was higher in the comparative thesis (CvtA in four of the five tested farms),
510 while the indicator of economic efficiency suggests the opportunity of using conservative farming
511 practices, especially in paddy rice production and in farms in which the introduction of conservative
512 practices is before 2006. The overall reduction of costs and the increase in economic balance was
513 also reported by Hobbs et al. (2008) and Scopel et al. (2013). However, in the comparison of the
514 economic balance between CA and CvtA, some aspects might result in a reduced gain in economic
515 efficiency.

516 In Carpaneta, the management of cover crop during the first cropping season (2013-2014) and the
517 significantly lower production of maize caused a decrease in the indicator of economic efficiency in
518 NT compared to MT. However, in NT compared to MT there is a higher content of organic carbon
519 (+ 0.2%) and a higher final BFI. In a Long-term perspective, a solution aimed to reduce the cost of
520 cover crop seeds might be to use the grain of cereals produced on-farm (e.g., rye and wheat), in
521 rotation with purchased seeds (e.g., mustards, vetch, black oat, and tillage radish).

522 The opportunity of using on-farm seeds for enhancing the economic sustainability has been not
523 investigated and would offer a new solution in the cropping system designing. Generally, the most
524 critical aspect, which is also the most relevant environmental issue concerning CA, is the costs

525 associated with the purchase of herbicides, which was higher in NT than in CvtA. Weeds possibly
526 reduce crop yield while increasing management costs. Weeds control was referred as critical by
527 many authors (Scopel et al., 2013; Powlson et al., 2014; Stavi et al., 2016) since the economic
528 advantage due to the reduced tillage might be counterbalanced by higher costs for herbicides
529 purchase and spraying. Tabaglio and Gavazzi et al., 2009, reported a decrease in weed pressure in a
530 NT system after three years since the implementation in a maize-based system in the Po valley.
531 Another option could be to couple optical sensors to global positioning system information enable
532 to distinguish weeds from crops and in turn perform precision weed control (Westwood et al.,
533 2018), using a lower rate of herbicides.

534 **5. Conclusions**

535 The monitoring carried out in 2014 and in 2016 on 20 farms allowed not only to compare different
536 management approaches of the crop systems but also to evaluate the evolution in short to medium
537 term of the agro-environment aspect under examination. The results obtained in the present study
538 indicate the environmental and economic sustainability of the agronomic management adopted in
539 the different pedoclimatic conditions experienced on the 20 farms.

540 The comparison of the variables did not show a common trend between the farms as they represent
541 unique realities, located in different areas resulting in heterogeneity of the adopted practices. The
542 farms where conservation agriculture practices resulted in positive results of both soil fertility and
543 economic efficiency are those in which such practices were implemented long before the beginning
544 of the present study. Consequently, the optimization of the practices requires the acquisition of
545 knowledge and the development of technical skills. On farms in which conservation agriculture
546 practices were adopted after 2006, conservation agriculture was found to increase the percentage of
547 organic carbon content and the biological fertility index, with a higher extent than the conventional
548 systems, although grain yield was significantly lower by 15% on average.

549 Our results suggest that the adoption of conservation agriculture practices is feasible in the Po
550 valley environment. After an initial phase required for farmers to develop technical skills, it is
551 possible to reduce the yield gap between conservation and conventional systems. Policy support for
552 technical training in CA is needed and should be reinforced at farm and district scales. Conversely,
553 the lack of a technical support might result in the abandoning of CA practices with a return to
554 conventional systems after the end of the 2014-2020 European subsidies program. Moreover,
555 involving farmers with the participatory approach in defining the strategies to adopt at field and
556 farm scale is regarded as fundamental for the effectiveness of their implementation (Nguyen et al.,
557 2016; Schindler et. al., 2016). As already suggested by Pradhan et al. (2017), institutionalizing CA
558 into regional institutions will enhance the sustainability of the technology. A side effect of the
559 present study was to connect farmers, even from different areas of the wide Po plain by adopting a
560 participatory approach involving scientists, technical professionals from both public agencies and
561 private sector, and policy makers.

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Tables

Table 1. Recent published reviews (2007-2017) concerning agro-environmental aspects related to the implementation of conservation tillage and cover crops in temperate areas. A synthetic result was retrieved from each review. The symbols '+', '-', and '=' indicate advantage, negative effect, and similar effect of conservation agriculture (CA) practices than the conventional agriculture (CvtA), respectively. Reviews on the same row had similar results of conservation tillage and cover crops effect. Some reviews dealt both with conservation tillage and cover crops; in this case two scores are assigned.

Conservation agriculture in comparison with conventional tillage			
	Conservation Tillage	Cover Crops	
Yield	= / -	=	Knowler and Bradshaw, 2007; Hobbs et al., 2008; Van den Putte et al., 2010; Stavi et al. 2016; Ranaivoson et al., 2017
	-		Ogle et al., 2012; Scopel et al., 2013; Powlson et al., 2014
		=	Blanco-Canqui et al., 2015
	-	+	Pittelkow et al., 2015
Farm management	+ / -		Farooq et al., 2011
		+	Delgado et al., 2007
	+		Hobbs et al., 2008; Scopel et al., 2013
	+ / -		Knowler and Bradshaw, 2007; Powlson et al., 2014; Ranaivoson et al., 2017
Weed management	+ / -		Armengot et al. 2015; Farooq et al., 2011
	-		Knowler and Bradshaw, 2007; Powlson et al., 2014; Ranaivoson et al., 2017; Stavi et al. 2016
Soil structure	+		Hobbs et al., 2008; Triplett and Dick, 2008; Morris et al., 2010; Abdalla et al., 2013; Powlson et al., 2014
		+	Blanco-Canqui et al., 2015
Nutrient use efficiency	+		Morris et al., 2010; Delgado et al., 2007
	+ / -	+	Scopel et al., 2013
		+	Quemada et al., 2013
Moisture retention/infiltration	+	+	Knowler and Bradshaw, 2007; Scopel et al., 2013
		+	Delgado et al., 2007; Blanco-Canqui et al., 2015
	+		Palm et al., 2014; Stavi et al. 2016
	+ / =		Ranaivoson et al., 2017
Soil temperature	+	+	Hobbs et al., 2008; Triplett and Dick, 2008; Morris et al., 2010; Scopel et al., 2013; Lal, 2015
	+		Virto et al., 2012; Abdalla et al., 2013; Stavi et al. 2016
Soil C sequestration	=		Powlson et al., 2016
	-		Ogle et al., 2012
		+	Delgado et al., 2007; Blanco-Canqui et al., 2015; Lal, 2015
	+ / =	+	Aguilera et al., 2013
	=	+ / =	Palm et al., 2014
	+ / =		Ranaivoson et al., 2017
	+ / = / -		Govaerts et al., 2009
Effect on GHGs emissions	+ / =		Palm et al., 2013; Abdalla et al., 2013
	=		Powlson et al., 2014
	+		Morris et al., 2010; Kaye and Quemada, 2017
Soil Biodiversity	+	+	Knowler and Bradshaw, 2007; Van Capelle et al., 2012; Powlson et al., 2014
	+		Triplett and Dick, 2008
Fuel consumption	+		Knowler and Bradshaw, 2007; Morris et al., 2010; Scopel et al., 2013; Powlson et al., 2014
Economic balance	+ / -		Knowler and Bradshaw, 2007; Pannell et al., 2014
		+ / -	Blanco-Canqui et al., 2015
	+ / =		Scopel et al., 2013
	+		Hobbs et al., 2008; Triplett and Dick, 2008

Table 2. Overall features of the farms involved in the present study. Conservation agriculture (CA) was implemented before 2006 (=Long-term), between 2006 and 2013 (=Medium-term), after 2013 (=Short-term). The CA agricultural system was NT (with exception of Cerutti and Don Bosco) and included the cultivation of winter cover crops. CA implied the cultivation of cover crops, except for the farms in Piedmont. CvtA=conventional system. CvtA=conventional system, MT=minimum tillage, NT=no-till.

	Administrative Italian Region	Farm	Location	Soil type	Year of CA implementation	Tested treatments	Crop rotation (2013-2016)						
							2013-2014	2014-2015	2015-2016				
CA vs CvtA	Emilia-Romagna	Cerzoo	45.01 N 9.71 E	Silty clay loam	2010 Medium-term	NT , CvtA	maize	soybean	w.wheat				
		Gli Ulivi	44.13 N 11.92 E	Clay	2015 Short-term	NT , CvtA	lucerne	w.wheat	sorghum				
		Ruozzi	44.71 N 10.77 E	Clay	2013 Short-term	NT , CvtA	w.wheat	maize	w.wheat				
	Friuli Venezia Giulia	La Fattoria	46.05 N 13.35 E	Loam	2006 Long-term	NT , CvtA	maize	soybean	barley - soybean				
	Lombardy	Arisi	45.15 N 10.16 E	Silt loam	2014 Short-term	NT , MT	maize	maize	soybean				
						CvtA	maize	maize	maize				
	Piedmont	Rossi	45.14 N 10.11 E	Silt loam	2010 Medium-term	NT	maize	w.wheat - soybean	w.wheat				
						CvtA	maize	maize	maize				
						MT , CvtA	maize	maize	maize				
	Veneto	Cerutti	44.94 N 7.90 E	Silt loam	2014 Short-term	MT , CvtA	maize	maize	maize				
						Don Bosco	44.88 N 7.69 E	Sandy loam	2006 Long-term	MT , CvtA	maize	w.wheat	maize
						Mosca	45.22 N 8.13 E	Sandy loam	2013 Short-term	NT, CvtA	rice	rice	rice
	Veneto	Diana	45.58 N 12.30 E	Loam	2009 Medium-term	NT , CvtA	maize	soybean	w.wheat				
						Pasti	45.56 N 12.76 E	Sandy clay loam	2005 Long-term	NT , CvtA	barley - soybean	maize	soybean
Sant'Ilario						45.40 N 12.15 E	Sandy clay loam	2008 Medium-term	NT , CvtA	maize	soybean	w.wheat	
Sasse Rami						45.05 N 11.89 E	Loam	2008 Medium-term	NT , CvtA	maize	soybean	w.wheat	
		Vallevecchia	45.63 N 12.94 E	Sandy loam	2008 Medium-term	NT , CvtA	maize	soybean	w.wheat				
CA (MT, NT)	Emilia-Romagna	Cavallini	44.67 N 12.76 E	Clay loam	2008 Medium-term	NT	w.wheat	soybean	w.wheat				
						NT	w.wheat	soybean	soybean				
	Friuli Venezia Giulia	Euroagricola	45.87 N 13.02 E	Silty clay loam	1998 Long-term	NT , NT	soybean	w.wheat	maize				
						Zanone	46.10 N 13.43 E	Silt loam	2010 Medium-term	NT , NT	sorghum	soybean	sorghum + soybean
	Lombardy	Carpaneta	45.19 N 10.88 E	Clay loam	2012 Medium-term	NT , MT	soybean	maize	w.wheat + clover				
						Grandi	45.09 N 9.20 E	Silty clay loam	2003 Long-term	NT , MT	maize	w.wheat	maize
		Rebollini	44.96 N 9.18 E	Loam	2015 Short-term	NT	lucerne	barley	buckwheat				
						NT	lucerne	barley	lucerne				

Table 3. Scores of the intervals of values for the different parameters and classes of the biological fertility index (BFI). TOC=soil organic carbon content (g kg^{-1}) estimated with the Springer-Klee method.

Parameter (or index)	Unit of measurement	Score ranges				
		1	2	3	4	5
Organic matter *	g kg^{-1}	<1	1-1.5	1.5-2	2-3	>3
Microbial organic carbon (MBC)	$\mu\text{g g}^{-1}$	<100	100-200	200-300	300-400	>400
Basal microbial respiration	$\text{mg CO}_2\text{-C h}^{-1} \text{kg}^{-1} \text{soil}$	<5	5-10	10-15	15-20	>20
Cumulative microbial respiration	$\text{mg CO}_2\text{-C h}^{-1} \text{kg}^{-1} \text{soil}$	<100	100-250	250-400	400-600	>600
Metabolic quotient	$\mu\text{g CO}_2\text{-C}_{\text{basal}} \text{h}^{-1} \mu\text{g}^{-1} \text{MBC}$	>0.4	0.3-0.4	0.2-0.3	0.1-0.2	<0.1
Mineralization quotient	$\mu\text{g CO}_2\text{-C}_{\text{cumulative}} \mu\text{g}^{-1} \text{TOC}$	<1	1-2	2-3	3-4	>4
Biological Fertility index	-	I 0-6 very low	II 6-12 low	III 13-18 average	IV 19-24 good	V 25-30 high

*Organic matter was calculated by multiplying TOC g kg^{-1} by 1.72

Table 4. Results of the linear mixed model applied to test the effects of the Agricultural_Systems (CA vs. CvtA) on the carbon-related variables, bulk density, biological fertility index, QBS-a, and earthworms count by using a repeated measure mixed model where the farm factor was nested within the Implementation_Year factor (Long-term=before 2006, Medium-term=from 2006 to 2013, Short-term=after 2013). Data were collected in the 14 farms where a comparison between CA and CvtA was established. CA=conservation agriculture, CvtA=conventional system.

Source	SOC Elemental Analyzer		Bulk Density		SOC Stock		TOC Springer- Klee		C-microbial biomass		Basal Respiration		Cumulative Respiration		Biological Fertility Index		QBS-ar		Earthworms			
	Num.	df	F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.		
Farm(Implementation_Year)	11		36.2	0.00	59.8	0.00	16.0	0.00	27.4	0.00	17.1	0.00	10.6	0.00	18.18	0.00	8.7	0.00	3.8	0.00	11.4	0.00
Implementation_Year	2		2.5	0.09	97.4	0.00	6.7	0.00	3.8	0.03	4.2	0.02	8.9	0.00	7.48	0.00	1.4	0.26	19.4	0.00	32.7	0.00
Agricultural_Systems	1		20.3	0.00	1.4	0.25	9.3	0.00	97.8	0.00	74.7	0.00	4.5	0.04	23.78	0.00	43.5	0.00	23.0	0.00	62.2	0.00
Agricultural_Systems x Implementation_Year	2		6.0	0.00	8.2	0.00	2.7	0.07	7.6	0.00	34.5	0.00	1.6	0.21	11.35	0.00	19.6	0.00	3.8	0.03	9.9	0.00
Agricultural_Systems x Farm	11		4.0	0.00	4.5	0.00	2.8	0.01	9.0	0.00	5.8	0.00	1.8	0.08	3.46	0.00	5.1	0.00	2.7	0.01	5.2	0.00

Table 5. Means of the carbon-related variables, bulk density, biological fertility index, QBS-a, and earthworms count. Means followed by different letters significantly differ (Sidak post-hoc test) between agricultural systems within implementation years. Data were collected in the 14 farms where a comparison between CA and CvtA was established. CA=conservation agriculture, CvtA=conventional system., Long-term=before 2006, Medium-term=from 2006 to 2013, Short-term=after 2013. N.=number of cases, S.D.=Standard deviation.

Implementation Year	Agricultural_systems:																			
	CA vs. CvtA																			
	SOC Elemental Analyzer		Bulk Density		SOC Stock		TOC Springer-Klee		C-microbial biomass		Basal Respiration		Cumulative Respiration		Biological Fertility Index		QBS-ar	Earthworms		
[g kg ⁻¹]		[Mg m ⁻³]		[Mg ha ⁻¹]		[g kg ⁻¹]		[µg g ⁻¹ dry soil]		[mg CO ₂ -C h ⁻¹ kg ⁻¹ soil]		[mg CO ₂ -C h ⁻¹ kg ⁻¹ soil]		[-]		[-]	[-]			
Long-term	15.3	14.7	1.41	1.40			17.1	15.5	192.0	174.8			310	277	17.8	16.7	69.9	61.2	18.5a	4.7b
	N. 18	N. 18	N. 18	N. 18			N. 18	N. 18	N. 18	N. 18			N. 18	N. 18	N. 18	N. 18	N. 18	N. 18	N. 18	N. 18
	S.D. 0.4	S.D. 0.5	S.D. 0.2	S.D. 0.2			S.D. 4.3	S.D. 4.3	S.D. 91	S.D. 116.3			S.D. 169.1	S.D. 143	S.D. 3.2	S.D. 2.4	S.D. 24.4	S.D. 15.7	S.D. 11.1	S.D. 4.7
Medium-term	16.6a	14.6b	1.26b	1.33a	61.9a	60.1b	16.1a	12.9b	203.9a	99.9b	6.7a	5.5b	345a	296b	19a	16.4b	90.6a	66.9b	14.8a	8.2b
	N. 36	N. 36	N. 36	N. 36	N. 90	N. 84	N. 36	N. 36	N. 36	N. 36	N. 90	N. 84	N. 36	N. 36	N. 36	N. 36	N. 36	N. 36	N. 36	N. 36
	S.D. 0.4	S.D. 0.3	S.D. 0.2	S.D. 0.2	S.D. 13	S.D. 12	S.D. 4.9	S.D. 2.8	S.D. 139.4	S.D. 51.7	S.D. 6.2	S.D. 4	S.D. 161.2	S.D. 138.4	S.D. 3.1	S.D. 3	S.D. 25.6	S.D. 26.6	S.D. 11.6	S.D. 9.3
Short-term	14.7	14.2	1.45	1.43			15.9	14.6	134.8	176.0			258	266	17.3	17.7	63.1	54.5	5.2	1.9
	N. 36	N. 30	N. 36	N. 30			N. 36	N. 30	N. 36	N. 30			N. 36	N. 30	N. 36	N. 30	N. 36	N. 30	N. 36	N. 30
	S.D. 0.3	S.D. 0.2	S.D. 0.1	S.D. 0.1			S.D. 2.5	S.D. 2.1	S.D. 65.2	S.D. 114.2			S.D. 85	S.D. 86.5	S.D. 2.1	S.D. 2.4	S.D. 23.4	S.D. 20.1	S.D. 7.4	S.D. 3.6

Table 6. Results of the linear mixed models applied to yield data. Agricultural_Systems (CA vs. CvtA), Implementation_Year (Long-term=before 2006, Medium-term=from 2006 to 2013, Short-term=after 2013), farm nested within the Implementation_Year. CA=NT, except for Cerutti and Don Bosco where it was MT, CvtA=plowing, except for Carpaneta, Grandi, where it was MT. Means followed by different letters significantly differ (Sidak post-hoc test) between agricultural systems and implementation years, separately. CA=conservation agriculture, CvtA=conventional system. N.=number of cases, S.D.=Standard deviation.

	Maize			Soybean			Winter Wheat			
	Num. Df	Den. Df	Sig.	Num. Df	Den. Df	Sig.	Num. Df	Den. Df	Sig.	
Farm(Implementation_Year)	10	33	0.11	7	29	0.10	5	14	0.02	
Implementation_Year	2	33	0.10	2	29	0.05	2	14	0.03	
Agricultural_System	1	33	0.07	1	29	0.01	1	14	0.51	
Agricultural_System x Implementation_Year	2	33	0.96	2	29	0.88	2	14	0.69	
Agricultural_System x Farm	9	33	0.54	5	29	0.67	4	14	0.61	
			Mean			Mean			Mean	
	N.	S.D.	[Mg ha ⁻¹]	N.	S.D.	[Mg ha ⁻¹]	N.	S.D.	[Mg ha ⁻¹]	
Agricultural_system:	CvtA	30	2.67	9.49	22	0.81	3.37 a	14	1.29	4.85
	CA	29	3.37	7.74	25	0.74	2.58 b	15	1.32	4.26
Group of Implementation_Year:	Long-term	14	3.01	10.2	16	0.76	2.99	4	0.53	4.5 b
	Medium-term	30	3.45	7.93	25	0.91	3.09	21	1.26	4.27 b
	Short-term	15	1.86	8.62	6	0.63	2.25	4	1.44	6.0 a

Table 7. Results of the simplified economic balance that was calculated to estimate (i) the costs associated to the raw material purchase (i.e. herbicides, crops seeds, mineral fertilizers, fungicides) and field operations (i.e. tillage, weeding, harvest, haying, slurry application), (ii) gross gain and the economic efficiency ratio (i.e. revenue from grain yield over direct costs). B=barley, M=maize, R=rice, S=soybean, W=winter wheat.

		Grain Yield [Mg ha ⁻¹]			Raw material purchase [€ ha ⁻¹]			Costs of field operations [€ ha ⁻¹]			Gross Gain [€ ha ⁻¹]			Economic Efficiency [€ ha ⁻¹ /€ ha ⁻¹]			
		2013-2014	2014-2015	2015-2016	2013-2014	2014-2015	2015-2016	2013-2014	2014-2015	2015-2016	2013-2014	2014-2015	2015-2016	2013-2014	2014-2015	2015-2016	
Carpaneta																	
NT	S	3.6	M 9.2	W 7.2	562	638	264	125	94	42	861	952	1027	2.3	2.3	4.4	
MT	S	3.7	M 10.2	W 6.9	375	429	269	78	117	117	1138	1321	891	3.5	3.4	3.3	
La Fattoria																	
NT	M	13	S 3.5	B 5.3	S 2.3	655	389	408	203	153	221	1567	963	1282	2.8	2.8	3.0
CvtA	M	14	S 3	B 5.4	S 3.2	822	367	408	303	212	319	1500	711	1589	2.3	2.2	3.2
Mosca																	
NT	R	5.4	R 4.9	R 5.2		185	185	142	108	111	104	1597	1419	1573	6.5	5.8	7.4
CvtA	R	6.2	R 6.3	R 5.9		185	185	142	164	161	158	1821	1859	1765	6.2	6.4	6.9
Pasti																	
NT	B	4.4	S 1.9	M 10.1	S 3.8	593	426	410	127	105	109	863	1317	1115	2.2	3.5	3.1
CvtA	B	3.2	S 3.2	M 11.1	S 3.8	503	397	238	125	145	123	1305	1490	1274	3.1	3.7	4.5
Ruozzi																	
NT	W	6.5	M 6.7	W 7.3		254	464	162	321	532	139	627	230	1050	2.1	1.2	4.5
CvtA	W	7.5	M 8.8	W 6.9		254	442	114	612	549	126	521	619	1037	1.6	1.6	5.3

Figure 1. Location in the Po Valley (Northern Italy) of the farms involved in the study.

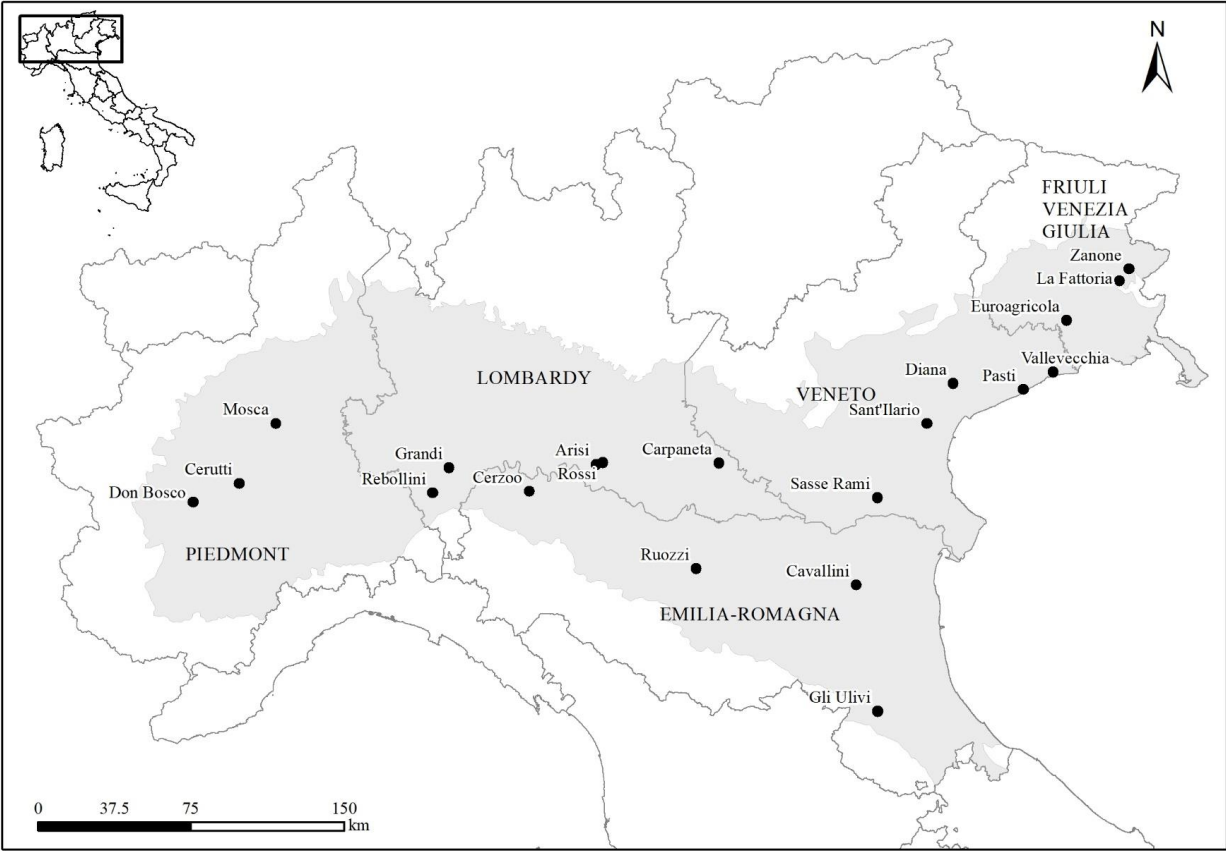


Figure 2a, 2b, 2c, 2d, 2e, 2f. Soil organic carbon (SOC) relative content stock, microbial biomass carbon, biological fertility index, QBS-ar, and number of earthworms observed in the topsoil (0-0.3 m) under the different combinations of tillage practices (CvtA, MT, NT) and Implementation_Year (Long-term=before 2006, Medium-term=from 2006 to 2013, Short-term=after 2013). Cross indicates the mean for each displayed combination. CvtA=conventional system, MT=minimum tillage, NT=no-till. CA=conservation agriculture, CvtA=conventional system. N.=number of cases, MSE=.mean standard error.

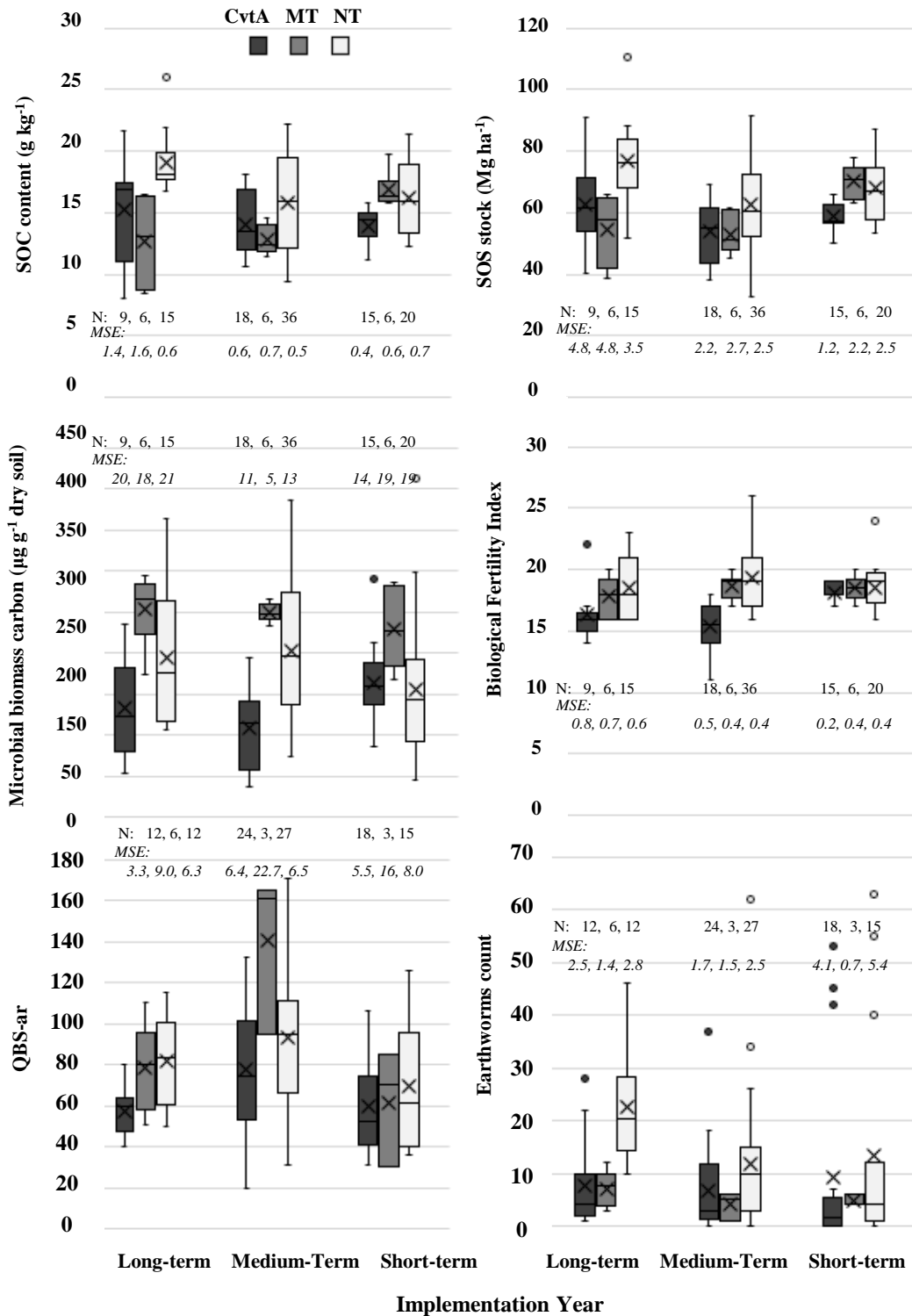


Figure 3. Relative effect of CA on SOC content and stock with respect to CvtA, expressed as $(SOC_{CvtA} - SOC_{CA}) / SOC_{CvtA}$ and $(STOCK_{CvtA} - STOCK_{CA}) / STOCK_{CvtA}$, which was calculated on 2016 data for each farm where a comparison was established. Data were then averaged by each Implementation_Year group. Bars are the confidence interval at 95%, which were calculated using the Z scores given the homogeneity of variance and the normal distribution. CA=conservation agriculture, CvtA=conventional system.

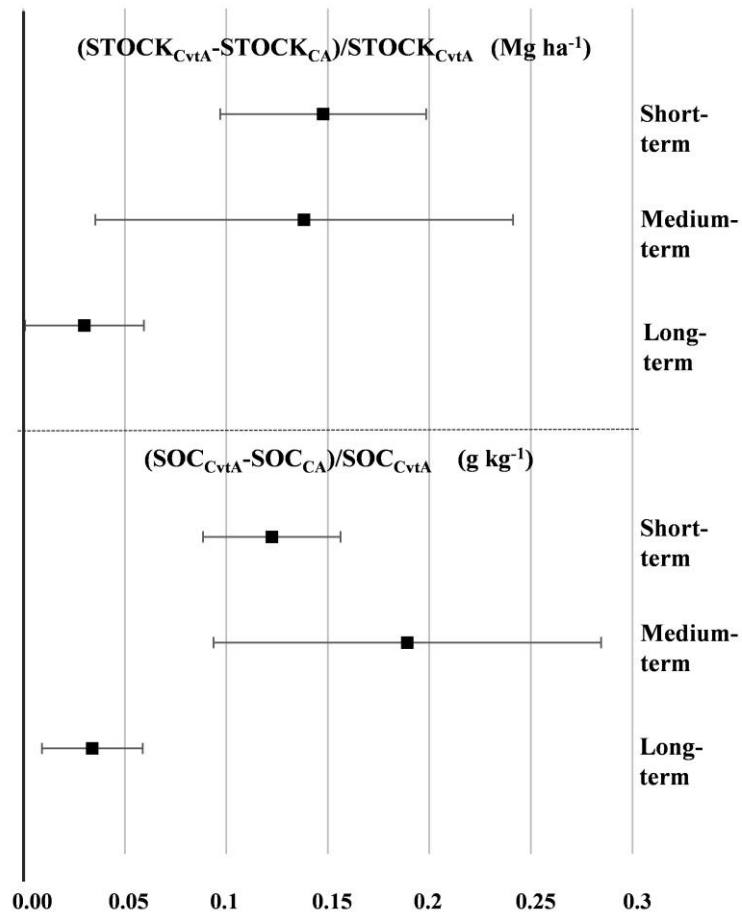


Figure 4. Exponential regression between the soil organic carbon content (TOC, measured via the Springer-Klee method) and the microbial cumulative respiration (samples collected in 2016 in topsoil, 0-0.3 m). The number of pairs is 131.

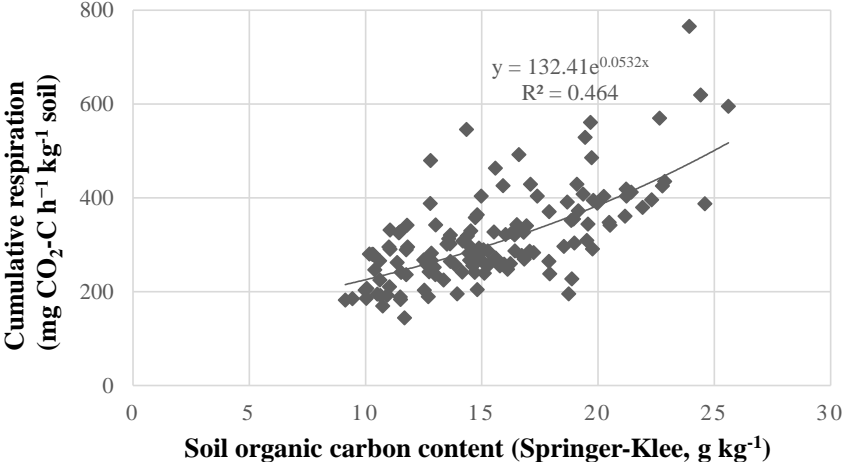


Figure 5. Number of cases of each Biological Fertility Index class in 2014 and 2016 for each tillage system (CvtA, MT, NT) and Implementation_Year group (long-term=before 2006, medium-term=from 2006 to 2013, short-term=after 2013). CvtA=conventional system, MT=minimum tillage, NT=no-till.

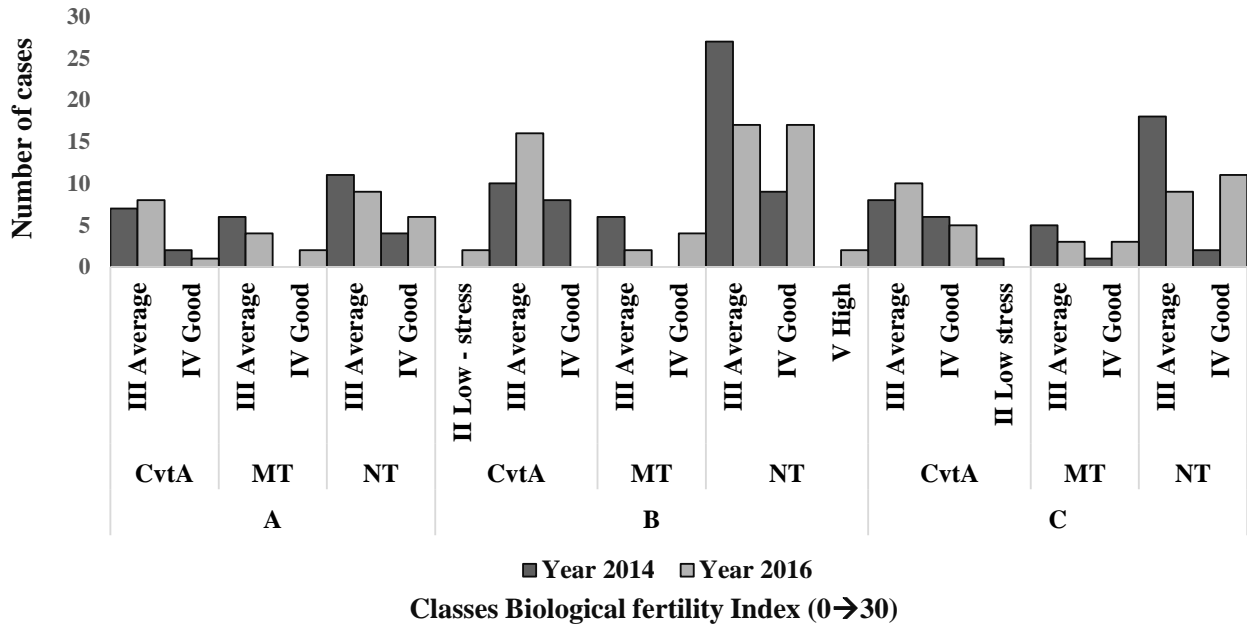


Figure 6. Grain yield of maize, winter wheat and soybean under CA (=NT, except for Cerutti and Don Bosco where it was MT) compared to CvtA (=plowing, except for Carpaneta, Grandi, where it was MT). Data are split by Implementation_Year (long-term=before 2006, medium-term=from 2006 to 2013, short-term=after 2013). Cross indicates the mean for each displayed combination. N=number of cases, MSE=mean standard error.

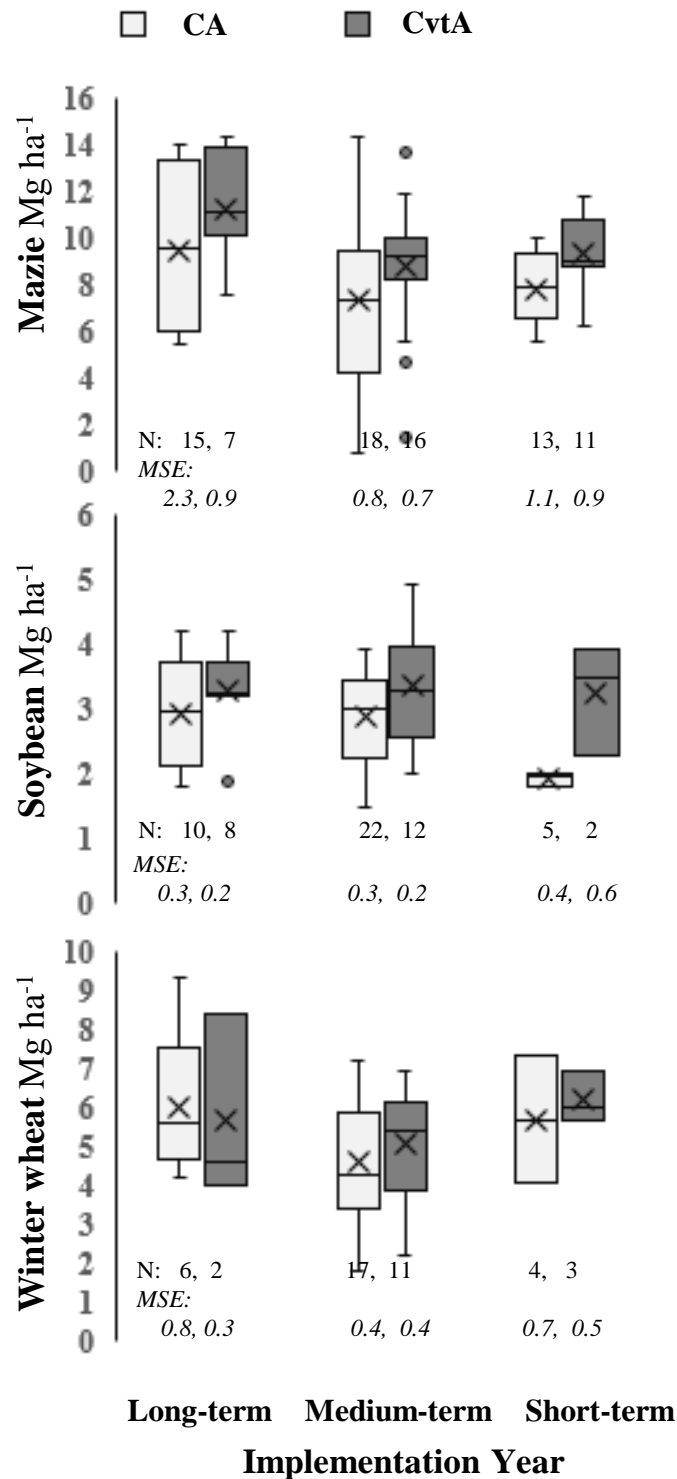


Figure 7. Tradeoff index: ratio of the variation in SOC stock over the variation in C-yield passing from CvtA to NT (from MT to NT in Arisi, Carpaneta, Grandi). CvtA=conventional system, MT=minimum tillage, NT=no-till.

