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

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Abstract

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

Highlights

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

1. Introduction

Agriculture is required to face major agro-environmental threats, such as the increasing carbon dioxide (CO_2) concentration in the atmosphere, decreasing biodiversity, and limited water availability (Bouma and McBratney, 2013); these processes can be effectively mitigated by an adequate management of the soil (McBratney et al., 2014). Conservation agriculture (CA), originally aimed at reducing water and wind erosion in the United States (Faulkner, 1943), was recently promoted by the Common Agricultural Policy of the European Union (CAP, Rural Development Programme 2014 -2020; Basch et al., 2011) to tackle the above mentioned agro-environmental issues (Armengot et al., 2016). CA consists in a set of agronomic practices, which includes: (1) minimal soil disturbance, performed through several techniques, i.e. minimum tillage (MT) and no-till (NT); (2) permanent soil cover that is ensured by retaining crop residues and (3) adopting crop rotations that include cover crops (Palm et al., 2014). Integrated nutrient management was indicated by Lal (2015) as another conceptual principle of the CA systems, obtained by nutrient recycling, biological nitrogen fixation, and cautious use of chemical fertilizers, contributing to a sustainable production system.

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

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

Evidence of a reduction of greenhouse gases emissions by CA has been reported by many authors (Morris et al., 2010; Corsi et al., 2012; Perego et al., 2016). Concerning the nitrous oxide, (N_2O) which is acknowledged as one of most potent gas in terms of warming potential, it was highlighted that CA has a similar or negative effect on N_2O emissions relative to CvtA (Abdalla et al., 2013; Palm et al., 2013; Powlson et al., 2014). Available data suggest that the switch from CA to CvtA practices is likely to enhance soil biodiversity (Knowler and Bradshaw, 2007; Powlson et al., 2014). In particular, Van Capelle et al., (2012), in a review focused on German data, found that, although microorganisms generally benefit from a reduction of tillage intensity, tillage effects on soil organisms vary according to soil texture, and therefore tillage system should be chosen on the basis of the local soil characteristics.

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

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

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

Recently, multiple studies have addressed CA in tropical, sub-tropical, and arid regions, with a focus on smallholder farmers (Giller et al., 2015; Brown et al. 2107a, Brown et al., 2017b, Farris et al., 2017). However, the implementation of CA in Europe (Soane et al., 2012), and in particular in Italy, is still an ongoing process whose environmental and economic feasibility needs to be evaluated. In Italy, CA is currently supported by the EU's CAP and the rural development programmes of the Italian administrative regions, such as the five regions laying in the Po valley (Piedmont, Lombardy, Emilia-Romagna) and Veneto and Friuli Venezia Giulia plain (Northern Italy). For simplicity, hereafter in the text, the entire flat area is referred to as Po valley. In this area, the organic carbon stock stored in the topsoil (i.e. 0.3 m depth) is 34 to 60 Mg ha^{-1} and the potential for further uptake is estimated to be at least 12.8 Mg ha^{-1} of CO_2 equivalent if soils are managed appropriately (Brenna et al., 2014). The Europe Commission funded the HelpSoil project (LIFE12 ENV/IT/000578), which was carried out on 20 farms in the Po valley and aimed at: i) strengthening the ecological functions of the soils (e.g. carbon sequestration, increase of fertility and edaphic biodiversity, protection against erosion); ii) evaluating the opportunity of coupling subsurface drill irrigation and no-till to enhance water use efficiency; iii) improving the nitrogen use efficiency while testing various fertilization techniques, in particular in the usage of livestock slurry; and iv) reducing the use of pesticides for the control of plant pests and diseases. The present study was set within the framework of the HelpSoil Project, under the assumption that only the on-site assessment of environmental and economic variables enables a sustainable adoption of CA practices. The study has the objective of evaluating the agro-environmental aspects (i.e., soil C-related variables, biological fertility, edaphic biodiversity, crop yield, and economic efficiency) in a direct comparison between CA and CvtA systems on working farms where CA practices have been implemented at different times.

2. Materials and methods

2.1. Study site and experimental design

Twenty farms were chosen within the Po valley in 2013 with the first aim of evenly representing the pedoclimatic conditions and cropping systems occurring in the area addressed by the HelpSoil project (Figure 1). The Po valley is a flat area and is approximatively 47000 km^2 wide; this area is characterized by peculiar traits that make it unique for a variety of meteorological and agricultural production systems variables (Fumagalli et al., 2013; Acutis et al., 2014). Climate is mild, the mid-latitude version of the Humid subtropical climate (Köppen climate classification Cfa and Cfb), and farming systems are generally intensive with high N input (Perego et al., 2013). The farms designated for the present study were characterized by different production systems, a broad range of soil properties, and critical issues to be addressed (e.g. low SOC content, weed pressure). Thus, the majority of the Agricultural_Systems under comparison were NT and CvtA, except for Cavallini, Rebollini, Euroagricola and Zanone farms (where only NT is present), Arisi (NT vs MT vs CvtA), Carpaneta and Grandi farms (NT vs MT), Don Bosco and Cerutti (MT vs CvtA). Such an experimental set up allows analyzing agro-environmental aspects under a wide range of technical and pedological conditions.

Over the course of the experiment, a varied range of meteorological conditions was recorded on the 20 farms involved in the project (Supplemental File 1); this aspect, along with the different pedological characteristics, allowed us to capture a wide variety of conditions in which both CA and CvtA practices were adopted. Mean annual rainfall from 2014 to 2016 varied from 709 mm (Ruozzi) to 1645 mm (La Fattoria, Zanone). The 20 locations also differed in mean annual temperature, which was the highest at Rossi (15.4 °C) and the lowest at Gli Ulivi (13.5 °C in 2016).

The monitoring on the demonstration farms was carried out from late 2013 to October 2016 (i.e. 32 months). The demonstration fields were set up on each farm with two or three replicates to compare production and environment-related aspects under the farm current condition (i.e. CvtA, MT or NT) and the CA alternative option (MT or NT). The farms' key features, such as site location, soil texture class, CA implementation year, crop rotation, and tillage treatments are listed in Table 2. Further details on cover crops cultivation and soil characteristics are given in Supplemental File 2.

The chemical and physical parameters of soils were measured on soil sampled in early 2014. Texture classes varied from sandy loam to clay; silty loam and silty clay loam were the soil types most represented in the present study. A different code was assigned to the farms where CA was implemented before 2006 (Long-term), from 2007 and 2013 (Medium-term), and at the beginning of the experiment in 2013 (Short-term); this temporal distinction was chosen following the findings of Pittelkow et al. (2015). Machinery with varied characteristics and brands were adopted for tillage and sowing, according to the on-farm availability and the tested tillage treatments. In an attempt to picture real farm conditions, dates of tillage, sowing, harvesting, weed and pest control, and irrigation were defined by local pedoclimatic conditions and farmers' experience.

Complete information about the 20 farms is given at the official project website *http://www.lifehelpsoil.eu/en/demonstrative-farms/.*

2.2. Data collection

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

Prior to the data collection in 2014, soils were sampled in each experimental field to determine soil texture, pH (in H_2O and KCl) cation exchange capacity, magnesium, calcium, and carbonate (total and active) content.

Soil samples (three independent replicates in each experimental field; 131 samples collected both in 2014 and in 2016) were collected at 0-0.3 m depth in each experimental field. The SOC content (g kg^{-1}) was determined both on air-dry subsamples of 40-mg weight (0.5 mm sieved) using a ThermoQuest NA1500 elemental analyzer (Carlo Erba, Milano, Italy) and with the Springer-Klee method (TOC) via oxidation with $K_2Cr_2O_7$ and subsequent titration of unreduced $Cr_2O_7^{-2}$ with $Fe(NH_4)_2(SO_4)^2$. The value measured by the former method was subtracted from the C-carbonate content, which was previously measured using a calcimeter. The latter method was employed as it is required for the estimation of the biological fertility index. In the present text, SOC content refers to the value estimated by the elemental analyzer.

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

$$SOC\ stock = SOC \times topsoil\ depth \times BD \times (RF) \times 10000\ m^2 \qquad [1]$$

where SOC (%) is the organic carbon content (%), *topsoil depth* is 0.3 m, BD is the topsoil bulk density (Mg m^{-3}), and *RF* is the rock fragment content (%). BD was estimated on a known volume soil sample, which was collected with a cylindrical metal sampler pressed into the soil to both 0.15 and 0.3 m depths (three replicates). The sample was oven-dried at 105°C and then weighed; the value of bulk density was calculated as the ratio of oven-dried mass over the soil sample volume (g cm^{-1}).

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

$$SOCratio = (SOC_{CvtA} - SOC_{CA}) \times SOC_{CVTA}^{-1} \qquad [2]$$

$$STOCKratio = (STOCK_{CvtA} - STOCK_{CA}) \times STOCK_{CVTA}^{-1}$$

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

Microbial biomass carbon (MBC, μg g^{-1} dry soil) was estimated via fumigation extraction, following the procedure detailed by Francaviglia et al. (2017). The cumulative microbial respiration was determined over 28 days of incubation by measuring the CO_2 emitted from a 20-g moist sample after 1, 3, 7, 10, 14, and 21 days. The cumulated CO_2 emitted from 21 to 28 days of incubation represented the basal respiration value. The following parameters and indices, which were derived from TOC and microbial-related measurements, were taken into account to calculate the BFI: organic matter OM (TOC × 1.72), MBC ($\mu g\ g^{-1}$ dry soil), cumulative respiration (mg CO_2-C $h^{-1}\ kg^{-1}$ soil), basal respiration (mg CO_2-C $h^{-1}\ kg^{-1}$ soil). The metabolic and mineralization quotients were calculated as follows:

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

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

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

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

The number of earthworms was counted on 15625 cm^3 (25 cm × 25 cm × 25 cm) undisturbed soil samples (FAO, 2008).

Also, for both the tested treatments on each farm, the aboveground biomass and crops grain yield were estimated by weighing the plants harvested on three areas of 5 m^2 in each experimental field and then pooled together. The biomass and grain dry matter content were obtained by weighing a 1-kg biomass subsample after 24 h at 105°C in a dry oven.

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

$$Tradeoff\ index = (SOC_{CA} - SOC_{CvtA}) \times (C\text{-}yield_{CA} - C\text{-}yield_{CvtA})^{-1} \qquad [5]$$

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

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

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

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

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

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

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

2.3. Statistical analysis

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

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

The linear mixed model was run by splitting the dataset by crop to investigate the effect of Agriculture_Systems and Implementation_Year on the grain production of the most common crops, namely maize, soybean, and winter wheat. For the other crops, less than two replicates across farms were available and, in turn, the related results were assumed to be insufficient for testing the effect of the Agriculture_System.

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

3. Results

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

3.1. Carbon-related variables

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

The analysis also showed a significant effect of the interaction between Agricultural_Systems and Implementation_Year on SOC content and BFI. Overall, the significant differences between CA and CvtA were found for the Medium-term group (Table 5). The first run of the linear mixed model highlighted a non-significant effect of the sampling depth on bulk density and consequently the mixed model was applied to the mean bulk density data, which were calculated as the mean between the two layers for each experimental field. The CvtA resulted in significantly higher bulk density than CA for the medium-term group. Farms, where BD in CvtA was higher than in CA, 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}), 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 content, SOC stock was significantly higher in CA than in CvtA for the Medium-term group. As for the significant interaction between farms and Implementation_Year, in two Medium-term and Short-term farms (i.e. Sasse Rami and Ruozzi), CA determined higher SOC stock in comparison with CvtA. A positive and significant contribution of CvtA in SOC stock was not found in any farm. Considering all of the collected data, including those on the farms where only CA was adopted, SOC content and stock were the highest in the Long-term group (Figure 2a, 2b).

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

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

Basal respiration was affected significantly by Agricultural_Systems and Implementation_year (Table 4). In particular, the lowest values were found in CA and for the Short-term group (5 mg CO_2-C h^{-1} kg^{-1} soil) compared with the Long-term (6.3 mg CO_2-C h^{-1} kg^{-1} soil) and the Medium-term (6.7 mg CO_2-C h^{-1} kg^{-1} soil) groups. The Agricultural_Systems × Implementation_year interaction was found significant for the cumulative respiration (i.e., higher in CA × Medium-term group). In two farms, the cumulative respiration was higher in CA than in CvtA (Sant'Ilario, 393 and 285 mg CO_2-C h^{-1} kg^{-1} soil; Vallevecchia: 395 and 237 mg CO_2-C h^{-1} kg^{-1} soil). The metabolic and mineralization quotients had a trend similar to that of TOC and cumulative respiration.

A positive linear correlation was detected between TOC and cumulative microbial respiration data collected in 2016 (Figure 4). At a SOC value higher than approximatively 18 g kg^{-1}, cumulative soil respiration rose steeply and in turn reduced the amount of the sequestered SOC.

BFI results were the highest under CA in the Medium-term group (Table 4). As for the tillage practices, BFI was higher in NT and MT compared to CvtA within the Long-term and Medium-term groups in 2016 (Figure 2d). Moreover, while distinguishing the evolution of the BFI by classes, Agricultural_Systems and Implementation_Year (Figure 5), the most relevant improvement in classes was found under NT and MT for the groups B and C, for which CvtA resulted in lower classes in 2016 than in 2014.

3.2. Microarthropods and earthworms

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

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

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

3.3. Grain yield

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

The tradeoff index (Mg C-soil ha^{-1}/Mg C-crop yield ha^{-1} y^{-1}) was calculated as the ratio of the SOC variation over the C-biomass yield variation between NT and CvtA with the aim of simultaneously considering the effect of the Agricultural_System on production and environment-related aspects. The tradeoff index varied significantly between farms (Figure 7). For eight farms, the index was negative as the increase in soil C stock offset the negative variation of C-yield production; these farms belonged to the Medium-term and Short-term Implementation_Year groups. A decrease in SOC stock and negative variation of C-yield production was estimated for five farms with no effect of Implementation_Year. An increase in SOC stock and a positive variation of C-yield production was calculated in the remaining four farms, which belong to the Short-term group (Arisi, index=2.05), the Medium-term group (Rossi, index=1.85), and the Long-term group (Grandi, index=2.57; La Fattoria, index=3.94).

3.4. Costs and fuel consumption

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

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

The fuel consumption and total cost of the sod-seeding in NT (on average, 9 L ha^{-1} and 20 € ha^{-1}) did not differ to those related to the seeding in CvtA (on average, 10 L ha^{-1} and 23 € ha^{-1}).

Considering the raw material purchase, the difference between NT and MT in Carpaneta in 2013-2014 was mainly due to the cover crops' seeds purchase (approximatively 25%). In La Fattoria the winter cover crop was barley, and the seeds costs represented only 3% of the annual costs for material purchase. Overall, the cost for herbicides' purchase was 18% more expensive in NT than in the comparative treatment, whereas the fuel consumption and total costs for weeding operations did not differ between NT and CvtA. The difference consisted in a higher number of weeding operation (1 to 2), which was due to the termination of the cover crops (in Carpaneta, Pasti, and Ruozzi) and to an additional intervention aimed to control a higher pressure of weeds (in Pasti and Ruozzi).

Crop yields, the gross margin and the indicator of economic efficiency for the treatments under comparison on the five examined farms are displayed in Table 7. Variation in gross gain was mainly driven by the differences in grain yield between treatments, which was generally lower in NT than in the comparative treatment (-0.5 Mg DM ha^{-1}). Consequently, the gross gain was generally lower in NT; conversely, the economic efficiency index was comparable and even higher in NT in La Fattoria.

4. Discussion

4.1 Soil-related variables

In the literature, findings are reported to support the capability of CA to result in positive changes in SOC content and stock compared to CvtA (Govaerts et al., 2009; Ogle et al., 2012; Virto et al., 2012; Abdalla et al., 2013; Stavi et al. 2016). The statistical analysis highlighted the significant effect of Implementation_Year × Agricultural_Systems on SOC storage, namely concentration and stock. CA within the Long-term and Short-term groups did not result in significantly higher SOC content and SOC stock (Table 5). However, this result did not inform about the gain in SOC storage that is achievable in CA compared to CvtA. The data of SOCratio and STOCKratio suggest that a significant SOC gain occurred for the three groups, especially for the Medium-term (Figure 3). This result agreed with the data reported by Tabaglio et al. (2008; 2009a; 2009b) from four trials in the Po valley. The SOCratio estimated in this study for the 0.3 m topsoil was higher than that shown by Powlson et al. (2014). The low results of the SOCratio and STOCKratio of the Long-term group was likely due to the low number of cases, and this is because farms where the implementation year of CA is before 2006 are unlike to allocate fields to CvtA practices. Also, in one farm belonging to the Long-term group (i.e. Pasti), tillage in CvtA consisted of moderate plowing, as confirmed by the low field operation costs (Table 7). Nonetheless, considering data collected under NT, also on farms where CvtA practices were not performed, the long-term contribution of NT on SOC content and stock is evident (Figure 2a and 2b).

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

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

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

4.2 Crop yield and tradeoff index

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

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

4.3 Costs and energy balance

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

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

The opportunity of using on-farm seeds for enhancing the economic sustainability has been not investigated and would offer a new solution in the cropping system designing. Generally, the most critical aspect, which is also the most relevant environmental issue concerning CA, is the costs associated with the purchase of herbicides, which was higher in NT than in CvtA. Weeds possibly reduce crop yield while increasing management costs. Weeds control was referred as critical by many authors (Scopel et al., 2013; Powlson et al., 2014; Stavi et al., 2016) since the economic advantage due to the reduced tillage might be counterbalanced by higher costs for herbicides purchase and spraying. Tabaglio and Gavazzi et al., 2009, reported a decrease in weed pressure in a NT system after three years since the implementation in a maize-based system in the Po valley. Another option could be to couple optical sensors to global positioning system information enable to distinguish weeds from crops and in turn perform precision weed control (Westwood et al., 2018), using a lower rate of herbicides.

5. Conclusions

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

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

Our results suggest that the adoption of conservation agriculture practices is feasible in the Po valley environment. After an initial phase required for farmers to develop technical skills, it is possible to reduce the yield gap between conservation and conventional systems. Policy support for technical training in CA is needed and should be reinforced at farm and district scales. Conversely, the lack of a technical support might result in the abandoning of CA practices with a return to conventional systems after the end of the 2014-2020 European subsidies program. Moreover, involving farmers with the participatory approach in defining the strategies to adopt at field and farm scale is regarded as fundamental for the effectiveness of their implementation (Nguyen et al., 2016; Schindler et. al., 2016). As already suggested by Pradhan et al. (2017), institutionalizing CA into regional institutions will enhance the sustainability of the technology. A side effect of the present study was to connect farmers, even from different areas of the wide Po plain by adopting a participatory approach involving scientists, technical professionals from both public agencies and 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
	+ / -		Farooq et al., 2011
		+	Delgado et al., 2007
Farm management	+		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
Soil C sequestration	+		Virto et al., 2012; Abdalla et al., 2013; Stavi et al. 2016
	=		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.

	Administative 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
		Rossi	45.14 N 10.11 E	Silt loam	2010 Medium-term	NT	maize	w.wheat - soybean	w.wheat
						CvtA	maize	maize	maize
	Piedmont	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.

		Score ranges				
Parameter (or index)	Unit of measurement	1	2	3	4	5
Organic matter *	g kg^{-1}	<1	1-1.5	1.5-2	2-3	>3
Microbial organic carbon (MBC)	µg g^{-1}	<100	100-200	200-300	300-400	>400
Basal microbial respiration	mg CO_2-C h^{-1} kg^{-1} soil	<5	5-10	10-15	15-20	>20
Cumulative microbial respiration	mg CO_2-C h^{-1} kg^{-1} soil	<100	100-250	250-400	400-600	>600
Metabolic quotient	µg CO_2-C_{basal} h^{-1} µg^{-1} MBC	>0.4	0.3-0.4	0.2-0.3	0.1-0.2	<0.1
Mineralization quotient	µg CO_2-$C_{cumulative}$ µg^{-1} TOC	<1	1-2	2-3	3-4	>4
Biological Fertility index	-	I	II	III	IV	V
		0-6	6-12	13-18	19-24	25-30
		very low	low	average	good	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.	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.

	Agricultural_systems: CA vs. CvtA																			
Implementation Year	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, exceptfor 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
		N.	S.D.	Mean [Mg ha^{-1}]	N.	S.D.	Mean [Mg ha^{-1}]	N.	S.D.	Mean [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.

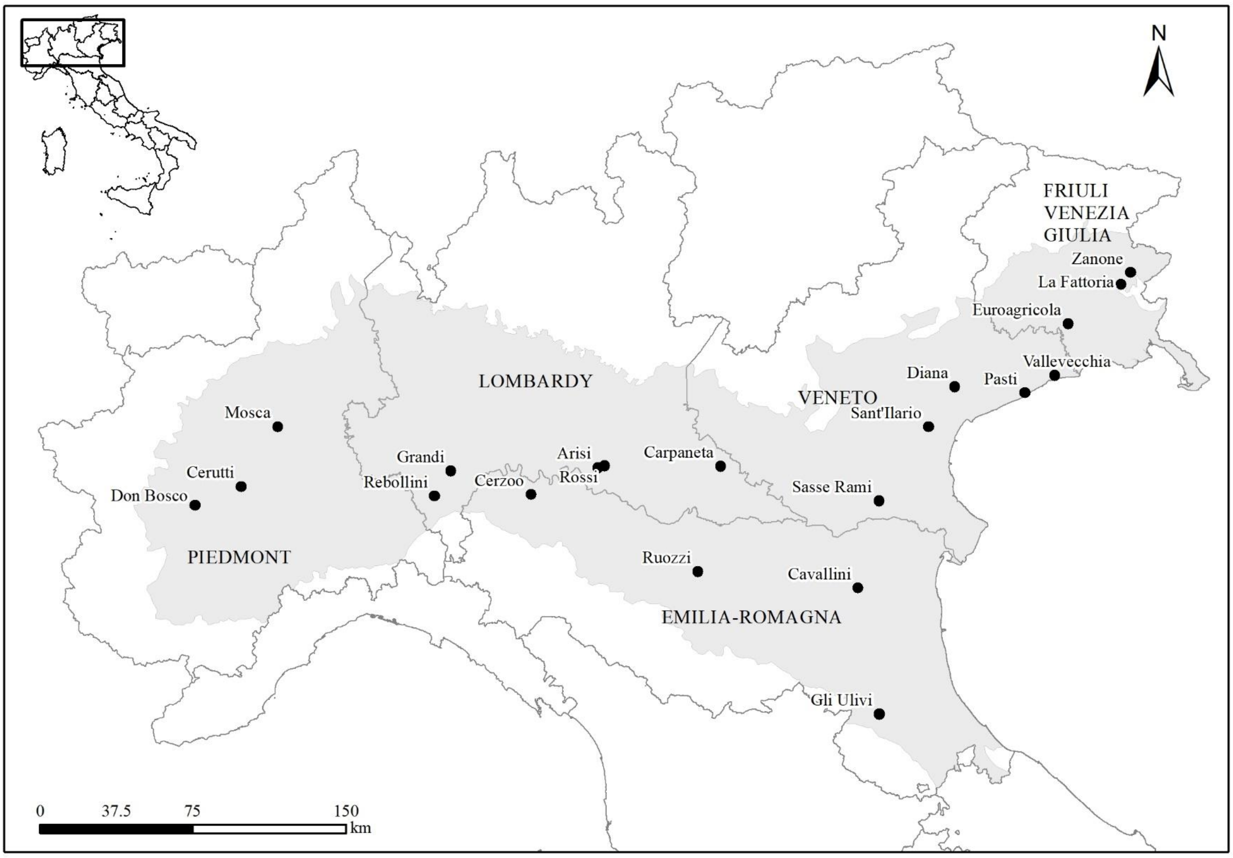

Figure 2a, 2b, 2c, 2d, 2e, 2f. Soil organic carbon (SOC) relative content stock, microbial biomass carbon, biological fertility index, QBS-ar, and number of earthworms observed in the topsoil (0-0.3 m) under the different combinations of tillage practices (CvtA, MT, NT) and Implementation_Year (Long-term=before 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.

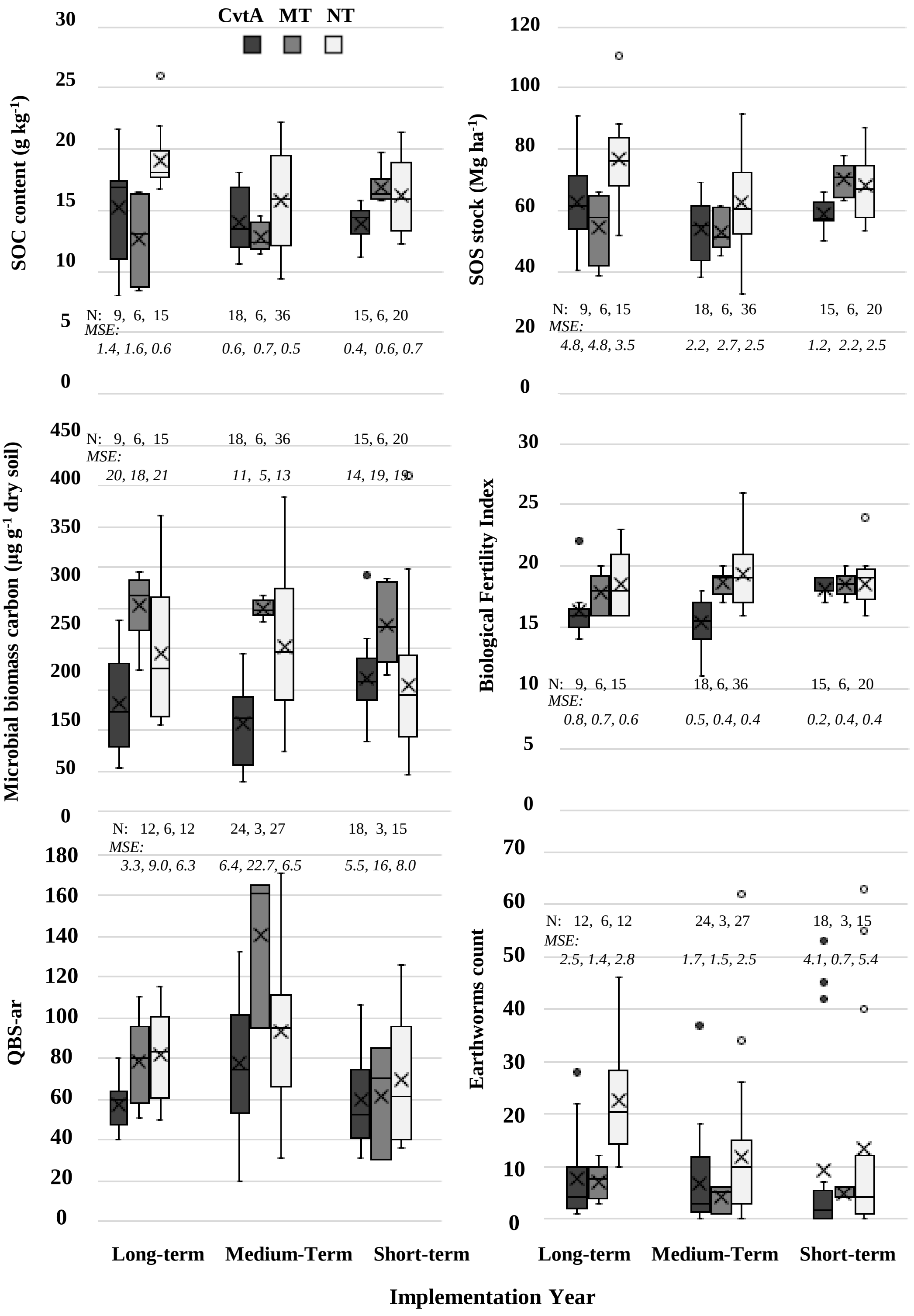

Figure 3. Relative effect of CA on SOC content and stock with respect to CvtA, expressed as $(SOC_{CvtA}-SOC_{CA})/SOC_{CvtA}$ and $(STOCK_{CvtA}-STOCK_{CA})/STOCK_{CvtA}$, which was calculated on 2016 data for each farm where a comparison was established. Data were then averaged by each Implementation_Year 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.

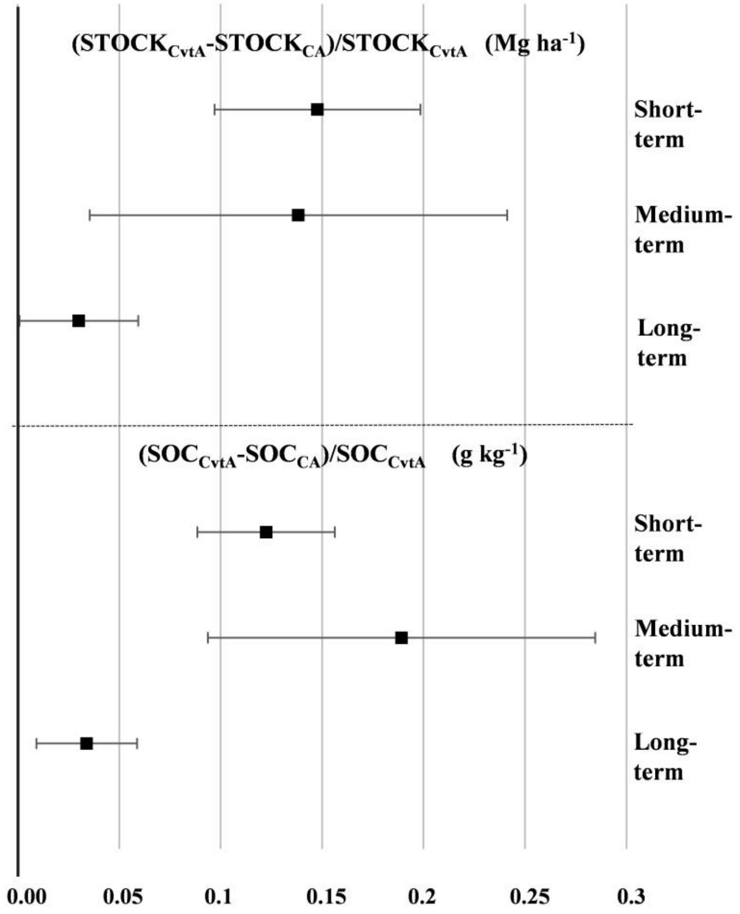

Figure 4. Exponential regression between the soil organic carbon content (TOC, measured via the Springer-Klee method) and the microbial cumulative respiration (samples collected in 2016 in topsoil, 0-0.3 m). The number of pairs is 131.

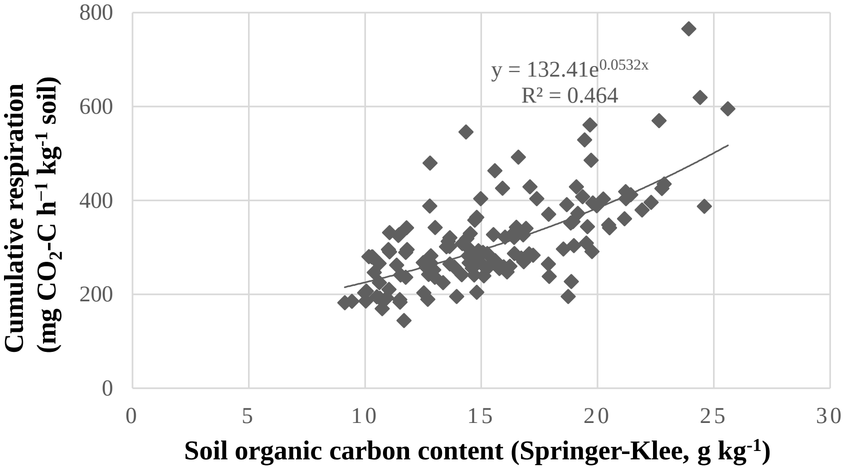

Figure 5. Number of cases of each Biological Fertility Index class in 2014 and 2016 for each tillage system (CvtA, MT, NT) and Implementation_Year group (long-term=before 2006, medium-term=from 2006 to 2013, short-term=after 2013). CvtA=conventional system, MT=minimum tillage, NT=no-till.

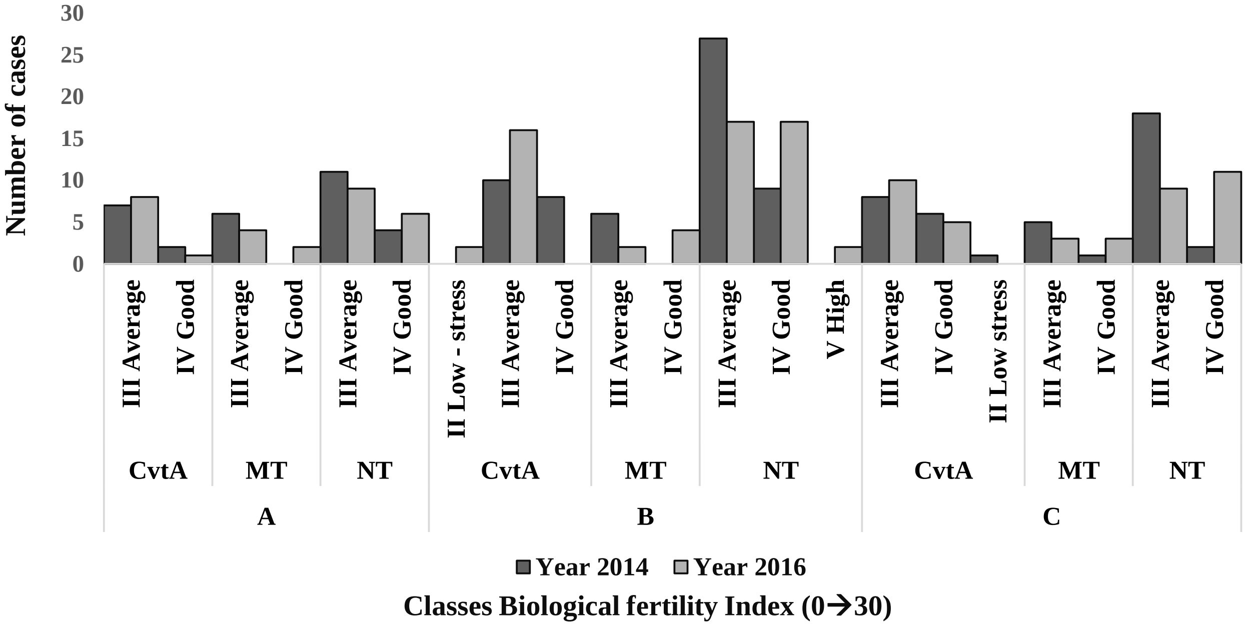

Figure 6. Grain yield of maize, winter wheat and soybean under CA (=NT, except for Cerutti and Don Bosco where it was MT) compared to CvtA (=plowing, except for Carpaneta, Grandi, where it was MT). Data are split by Implementation_Year (long-term=before 2006, medium-term=from 2006 to 2013, short-term=after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

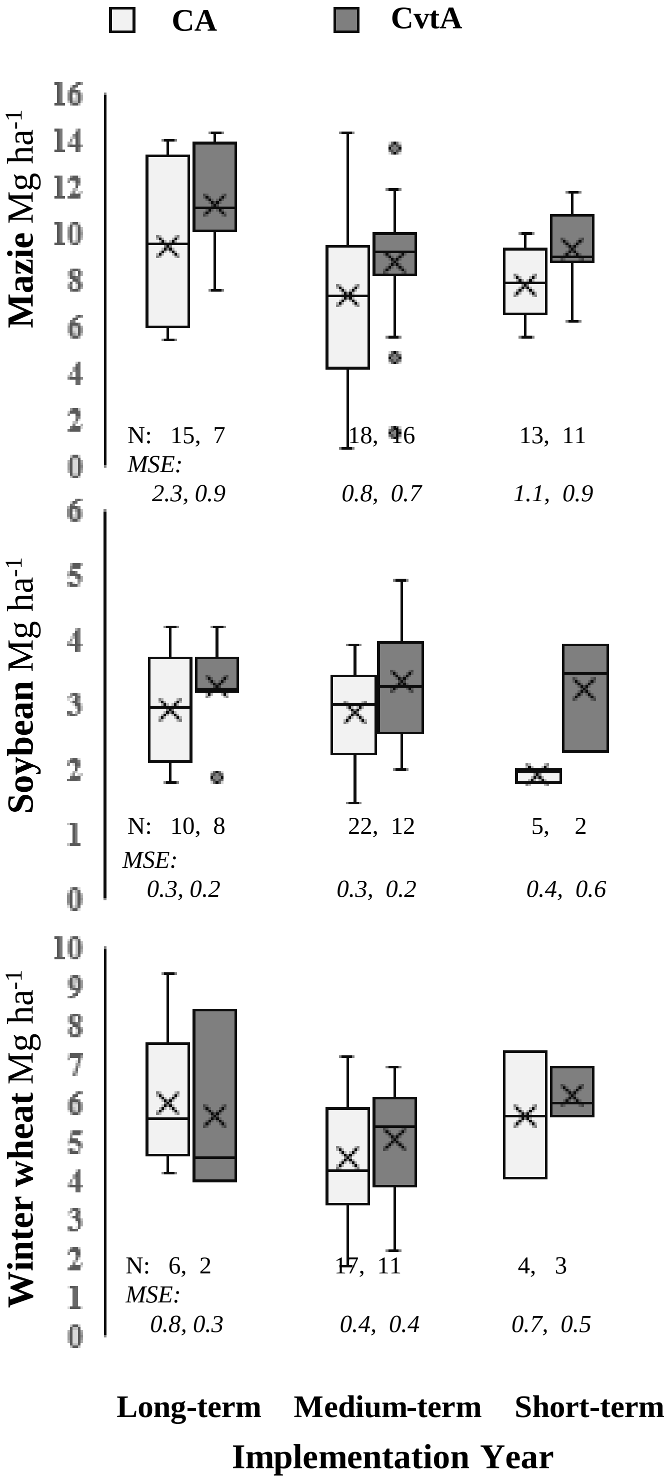

Figure 7. Tradeoff index: ratio of the variation in SOC stock over the variation in C-yield passing from CvtA to NT (from MT to NT in Arisi, Carpaneta, Grandi). CvtA=conventional system, MT=minimum tillage, NT=no-till.