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Short-term crop and soil response to C-friendly strategies in two contrasting environments

Francesco Alluvione[1], Nunzio Fiorentino[2*], Chiara Bertora[1], Laura Zavattaro[1], Massimo Fagnano[2], Fabrizio Quaglietta Chiarandà[2], Carlo Grignani[1]

[1]Dipartimento di Agronomia, Selvicoltura e Gestione del Territorio – Università di Torino

[2]Dipartimento di Ingegneria Agraria e Agronomia del Territorio – Università di Napoli Federico II

*Corresponding author.

Dipartimento di Ingegneria Agraria e Agronomia del Territorio, Università di Napoli Federico II
via Università 100, 80055 Portici, Italy.
Phone: +39 0812539129
Fax: +39 0812539155
email: nunzio.fiorentino@unina.it

Abstract

In southern Europe (Italy), a two-site field experiment with contrasting soil conditions (high clay—SOC-protecting soil near Napoli versus low clay—non-SOC-protecting soil near Torino) was conducted to evaluate the short-term potential of a carbon (C) friendly management to sustain and possibly increase both crop yields and soil organic C (SOC). Compost distribution (COM1, COM2) and minimum tillage (MT) were compared to conventional management (CONV) in a maize-based cropping system. COM1, MT, and CONV each received 130 kg N ha−1 in compost or urea form. A double dose was applied to COM2 while the plowed control plots (0 N) were not fertilized. Fertilizers were applied for three years (from 2006 to 2008); residual soil fertility was assessed during the fourth year (2009).

Results suggested that only the SOC protection strategy via MT could be agronomically sustainable in the high clay content soil near Napoli. There, a short-term SOC increase was recorded with either compost or MT application. In fact, in the same soil, compost use depressed both yield and N availability for maize, which we attribute to the reduction of SOM mineralization due to hydrophobic protection by added humified organic matter coupled with soil physical protection. Compost addition increased SOC (55.1% of added C) in the soil near Torino, where high native N availability buffered its low mineralization and allowed high yields. Alternatively, MT showed no effect on short-term C dynamics, probably because the low organic matter protection favored oxidation and mineralization of root-derived C.

Keywords

compost; minimum tillage; maize; mineralization; short-term C dynamics; SOC physical protection.

1. Introduction

In recent decades, wide scientific debate has highlighted the need to preserve and restore soil organic matter (SOM) (Bot and Benites, 2005; Lal, 2009, 2011) and fertility (Johnston, 1991; Bauer and Black, 1994; Doran and Parking, 1994) with the aim to improve soil ecosystem functions (Manlay et al., 2007; Mondini and Sequi, 2008) and atmospheric CO2 sequestration into SOM (IPCC, 2007b). Acknowledged by environmental stakeholders (Brown, 1984; Bot and Benites, 2005; Scherr and Sthapit, 2009), the science has been endorsed at both national and international levels. Among the most important examples are the ratification of the Kyoto Protocol (UNFCCC, 1997; IPCC, 2007a) and the adoption of the Conservation Reserve Program (CRP) in the USA (Follett, 2001) and the Common Agricultural Policy in the EU (European Council, 2005; European Community, 2009).

Agriculture is one of the major causes of SOC decline (Eswaran et al., 1993; Bruce et al., 1999; Guo and Gifford, 2002; Celik, 2005). It has not only reduced organic C inputs to the soil, but also increased mineralization of newly-added and old-stabilized organic matter (Lal, 2004) from soil disturbance. Soil tillage is the crop management technique that impacts SOM degradation highly since it can alter oxidative conditions (Alluvione et al., 2009) by disrupting soil structure and exposing soil aggregate C to microbial activity (Six et al., 2000; Pinheiro et al., 2004; Fagnano and Quaglietta Chiarandà, 2008). Therefore, the two main strategies to counterbalance SOC depletion (Paustian et al., 2000; Follett, 2001; Freibauer et al., 2004; Lal, 2008, 2009) are to increase C inputs or to decrease soil disturbance.

Increase C inputs

Fertilization can promote SOC sequestration through increased residue production (Halvorson et al., 1999; Follett, 2001; Alvarez, 2005) and C addition when organic fertilizers are used (Grignani et al., 2007; Melero et al., 2007; Triberti et al., 2008). Moreover, adding stabilized organic matter (i.e. compost) can enhance humification through several means: augmentation of recalcitrant compounds (Dick and Gregorich, 2004; Bertora et al., 2009); protection of stabilized SOM (Spaccini et al., 2002; Piccolo et al., 2004; Lynch et al., 2006); chemical modification of SOM (Spaccini et al., 2009); increased aggregate stability (Abiven et al., 2009; Diacono and Montemurro, 2010). Compost fertilization can exert other positive environmental effects. In particular, it not only reduces groundwater N pollution risk (Erhart et al., 2007) and greenhouse gas emissions (Ginting et al., 2003; Alluvione et al., 2010), but also it maximizes the amount of stabilized C (Bernal et al., 1998). Park or urban solid waste compost can substitute mineral-N fertilizers in some agro-ecosystems (Eriksen et al., 1999; Tejada and Gonzalez, 2003; Courtney and Mullen, 2008), but its effects must be verified in the specific pedo-climates where it is applied, as its low N mineralization rate (Claassen and Carey, 2004; Bowden et al., 2007; Diacono and Montemurro, 2010) might depress crop growth (Leroy et al., 2007). At the local level, municipal solid waste (MSW) composting has become an important way of recycling organic matter and plant nutrients (Ikumo, 2005; Erhart et al., 2007; Courtney and Mullen, 2008; Hargreaves et al., 2008) and to divert wastes from landfills (Gigliotti et al., 1996; European Commission, 2000; Hargreaves et al., 2008), although the potential for metal and organic pollution must be considered (Moreno et al., 1996; Düring and Gäth, 2002; Jordão et al., 2003; Fagnano et al., 2011).

Decrease soil disturbance

Conservation tillage techniques, aimed at minimizing soil inversion and soil structure disruption, increase SOM by reducing residue and organic matter oxidation (Lal and Kimble, 1997; West and Post, 2002; Holland, 2004; Alluvione et al., 2009). Although uncertainty remains as to the SOC-sequestering efficacy of such techniques given the limited potential for C accumulation in different soil layers (Baker et al., 2007; Lal, 2009; Luo et al., 2010), there is no doubt about their fossil fuel-saving benefit. Conservation tillage techniques are many and varied: no-till, strip tillage, and minimum tillage (increasing level of soil disturbance). Soil organic matter accumulation from no-till can, in fact, be larger than that obtained using minimum tillage, (Hernanz et al., 2009; Sombrero and de Benito, 2010; López-Fando and Pardo, 2011); however, minimum tillage has applicability to a wide range of pedoclimatic situations and creates better conditions for seed germination and pest control (Van den Putte et al., 2010).

C-friendly agronomic practices can be adopted by farmers if yields are comparable to those obtained in business-as-usual practices (Freibauer et al., 2004). Furthermore, since soil C sequestration-promoting methods interfere with nutrient cycling and water balance, alternative tillage (Six et al., 2002; Hutchinson et al., 2007; Morris et al., 2010; Mazzoncini et al., 2011) and fertilization (Alvarez, 2005) techniques must be chosen based on the specific pedo-climate and cropping system in use (Luo et al., 2010). In particular, positive outcomes are not as obvious in Mediterranean climates, especially with regard to crop development. High summer temperatures coupled with low precipitation (JRC, 2001) strongly affect nutrient and water availability, microbial activity, and crop development. Nonetheless, soils from Mediterranean pedo-climates are among those that can benefit most from strategies to increase soil organic matter because of their typically low SOM starting levels (JRC, 2001; Zdruli et al., 2004; Ryan et al., 2009; Diacono and Montemurro, 2010).

Research that evaluates the strategies of adding or protecting SOC side-by-side, under differing pedo-climates, would therefore assess the best agronomic and environmental outcomes (Dam et al., 2005). To this end, we designed a field experiment that included three objectives. Our first goal was to assess the applicability of alternative C- friendly strategies aimed at increasing soil organic matter or reduce its oxidation—either addition of stabilized organic matter in the form of compost or adoption of minimum tillage. Strategy success was evaluated by the ability of each to support maize yields, crop N nutrition, and short-term soil fertility. Our second goal was to evaluate the potential of tested strategies to positively affect short-term C dynamics. Our third goal was to identify guidelines to assist in the selection of C sequestration strategies more suitable for different pedo-climatic conditions. Using two southern European soils from different pedo-climatic conditions, we tested the following hypotheses:

(i) Minimum Tillage or compost fertilization are agronomically sustainable since they support maize growth at levels similar to traditional moldboard plowing coupled with urea fertilization;

(ii) Minimum Tillage and fertilization with compost positively affect short-term soil C dynamics;

(iii) the ability of a C-friendly strategy to sustain maize growth is driven by soil properties.

2. Materials and Methods

2.1 Study sites

The field trials were carried out in two contrasting pedoclimates in Italy belonging to the mesothermal climate family (Strahler and Strahler, 1984). The chosen sites were exemplary of typical agricultural pedo-climates of southern Europe. Site TO, located in the Po River Valley near Torino (44◦53 N, 7◦41 E, 232 m a.s.l.), belongs to climate type F (hot temperate climate without dry season, similar to temperate climates). Its long-term average yearly temperature is 11.9 ◦C, and the long-term average yearly precipitation is 734 mm, characterized by two main rainfall periods: spring (April–May) and autumn (September–November). Site NA, located in a coastal plain of southern Italy, specifically the Sele River Plain near Napoli (40◦37 N, 14◦58 E, 30 m a.s.l.), belongs to climate type S (hot temperate climate with dry summer, also called Mediterranean climate). In this case, the long-term average yearly temperature is 15.5 ◦C, and the long-term average yearly precipitation is 908 mm, with a peak in autumn-winter and a very dry summer. A more extensive description of the meteorological conditions of the two study sites can be found in Grignani et al. (2012). Soil properties differed at the two sites—Typic Ustifluvent in TO and Vertic Haploxeralf in NA. Selected chemical and physical properties of the plowed layer (0–30 cm) in 2006 are reported in Table 1 for TO and NA. In particular, TO soil (silty loam texture) had lower clay content, lower bulk density, and higher SOM than NA soil (sandy clay loam texture).

2.2 Treatments and experimental design

We tested the following treatments:

(i) conventional (CONV) moldboard plowing at 30 cm, mineral fertilization with urea (130 kg N ha−1);

(ii) minimum tillage (MT) by rotary harrow, mineral fertilization with urea (130 kg N ha−1);

(iv) compost (park, garden, and separately collected urban waste mixture) fertilization at two doses (COM1 and COM2, 130 kg N ha−1 and 260 kg N ha−1, respectively) followed by soil incorporation with moldboard plow at 30 cm; and

(v) non-N-fertilized control (0 N) moldboard plowed at 30 cm.

Since the urea was immediately incorporated into the soil after its distribution, we considered ammonia volatilization to be null. The experimental design was completely randomized with four replicates and 48 m2 (6 m×8 m) plots at TO and a completely randomized block with four replicates and 30 m2 (6 m × 5 m) plots at NA. We chose to grow maize (Zea mays L.) because its high N demand amplifies the treatment effects. Similarly, we set fertilization levels below crop requirements (Zavattaro et al., 2012) to emphasize treatment effect differentiation on N uptake levels. Though it is commonly recognized that only a small fraction of applied N from compost is available to the subsequent crop (Eriksen et al., 1999; Amlinger et al., 2003; Bowden et al., 2007; Hargreaves et al., 2008), we applied the same amount of total N via compost as we did via urea to allow comparison of their N efficiency. Field trials were carried out during four consecutive years from 2006 to 2009. The preceding crops were sorghum and maize at the TO and NA site, respectively. To evaluate the management effect on crop and soil organic matter, treatments were repeated on the same plots from 2006 to 2008 as previously described. To assess soil fertility changes achieved by the different treatments during the previous years, no N fertilizer was applied in 2009 and crop development was used as a proxy for residual soil fertility.

2.3 Crop management

Fertilizers were distributed and incorporated on the same day just before seedbed preparation. Compost was collected at the beginning of the experiment (2006), stored in 30 kg plastic bags and used at both locations during the three consecutive cropping seasons. It remained stable and fully mature with a C:N ratio <20 (Chefetz et al., 1996; Brinton, 2000; Silva et al., 2007), and was not phytotoxic at the 150 Mg $ha-1$ rate used for the plant growth assay of Chukwujindu et al. (2006) suggested by Astori (1998). Compost chemical composition, especially C, N, and moisture content, slightly varied during the experimentation period and its key chemical parameters are reported in Table 2. P and K fertilization ($P2O5$ = 100 kg $ha-1$ as triple superphosphate; $K2O$ = 200 kg $ha-1$ as muriate of potash) were the same for all plots.

All treatments were moldboard plowed at 30 cm (except MT) and two passes of the rotary hoe were used to prepare the seedbed (including MT); maize was sown according to a density of 7.4 seeds per m2. A traveling-gun sprinkler irrigation system provided water at TO while a drip irrigation tape system was used at NA site. Watering was made weekly with a water amount calculated from reference evapotranspiration (Hargreaves and Samani, 1985) and maize crop coefficients (Allen et al., 1998). A post-emergence weed control was used for all the treatments. Water quality was not significantly different at the two sites, with the following average parameters: pH = 7.4, EC = 1.02 dS $m-1$, $NO3 -$ = 2.3 ppm. Agronomic operations are reported in Table 3, while a more detailed description can be found in Alluvione et al. (2010). The crop aboveground biomass was entirely removed at harvest.

2.4 Measured parameters

Treatment effects were evaluated through several indicators and monitoring methods: (i) crop development (agronomic sustainability) through maize yields and N uptake, (ii) short-term soil fertility through soil $NO3 -$-N evolution during the cropping seasons, and (iii) short-term soil fertility dynamics through organic C and total N evolution during the first three years.

Total biomass and N uptake were assessed by hand-harvesting at dent stage from an area of 15 m2 (5 m in 4 rows with 0.75 m interrow spacing) per plot. Plant samples were oven-dried at 70 ◦C until a constant weight. The C and N tissue contents were measured using a CHN elemental analyzer (NA 1500 N analyzer from Carlo Erba Instruments, Thermo Fisher Scientific, Waltham, MA).

NO3$^-$–N content (SN) was determined by collecting soil samples before sowing, at flowering, and after harvest from three soil layers (0–15, 15–30, 30–60 cm) in all plots and during all years. Pooled data on the 0–60 cm layer will be presented. At TO, soil nitrates were extracted by shaking 100 g of moist soil with 300 ml of 1 M KCl solution for 1 h. Subsequently, the samples were filtered through Whatman no. 1 paper and then frozen until NO3 −–N concentration analysis by colorimetry with a continuous flow analyzer (Evolution II, Alliance Analytical Inc., Menlo Park, CA). At NA, soil nitrates were extracted according to the Hach® method and the extracts were analyzed by spectrophotometry (Hach DR 2000, Hach Company, Loveland, CO).

Soil C and total N content was monitored by collecting soil samples from the 0–30 cm plowed layer before experimental start and after each annual harvest. Analyses were carried out on a pooled sample composed by three sampling points per plot. Organic C content was determined through chromic acid digestion (Walkley and Black, 1934) and Total N was determined using the same CHN elemental analyzer from Carlo Erba Instruments as above described.

2.5 Data Analysis

All variables (total harvested dry biomass, total N uptake, soil NO3 −–N content, variation in soil organic C, and total N content) were subjected to ANOVA, using SPSS 17.0 software (SPSS Inc., Chicago, IL). The treatments were considered as the main factor. When possible (total harvested dry biomass, total N uptake, soil NO3 −–N content), year effect was analyzed as a repeated measure. Site and crop stage were not included as factors in order to preserve homogeneity of variance, thus these data were analyzed separately. Normality of distribution and homogeneity of variance were verified using the Kolmogorov–Smirnov and Levene tests, respectively. Soil NO3 −–

N content was transformed through natural logarithm (of values added to 100 to eliminate 0 values) to preserve normality of distribution and homogeneity of variance before the ANOVA. When effects were significant, means were separated using the Sidak post hoc test. All statistical comparisons were made at the $\alpha = 0.05$ probability level. Average values of variables were compared between sites using a Student's t-test assuming unequal variances.

3. Results

3.1 Crop production and N uptake

Maize yields during the three years of treatment application (2006–2008) were affected by site and fertilization method (Table 4). We observed higher yields in TO as compared to NA. Compost fertilization significantly reduced total biomass production at NA while no effect was observed at TO. Minimum tillage had no effect in any of the two locations.

In terms of site effects, total biomass production in CONV was 22.5% higher (P(F) = 0.000) at TO than at NA (22.9 Mg ha^{-1} versus 18.7 Mg ha^{-1}, respectively). Annual mean values among treatments showed a significant decrease at both sites over time (Table 4) although the causes were different. At TO, yields were significantly lower in 2008 for all treatments due to hail injury. On the contrary, at NA, we observed a progressive reduction in urea-fertilized plots (from 21.9 Mg ha^{-1} to 15.5 Mg ha^{-1} in CONV) while compost yields were constantly low. In the control plots (0 N), biomass yield did not differ from that of the reference urea fertilized plots (CONV) except in the second year at NA and in the third year at TO.

At NA, MT and CONV achieved the highest yields but, according to the LSD (Sidak) test, biomass production in MT did not differ across the years while in CONV it was lower in 2008. On the contrary, compost application, regardless of fertilization levels, produced the lowest but stable biomass across all years (three year average of 8.0 Mg ha^{-1}), with values significantly lower than 0 N (−61.6%) in 2006. Control plots were not significantly different from the urea treatments in 2006, but biomass production was halved in subsequent years with no yield differences in 2007 and 2008.

At TO, there were no significant maize yield differences among treatments in any year except for 2008 in the non-fertilized control, which yielded less than COM2, MT, and CONV.

The annual pattern of total N uptake was similar to that of total biomass (Table 4). N uptake was higher at TO than at NA. Tillage had no effect in any location. A site comparison showed that the N uptake three-year average in CONV was 27.5% higher (P(F) = 0.000) at TO than at NA (235.8 kg N ha^{-1} versus 185.0 kg N ha^{-1}, respectively). Annual mean values among treatments resulted in a significant decrease at both sites (from 261.3 to 160.0 kg N ha^{-1} at TO and from 156.1 to 85.4 kg N ha^{-1} at NA), primarily caused by progressive reductions in urea-fertilized treatments and in 0 N.

At NA, urea-fertilized treatments resulted in the highest N uptake levels (three-year average of 184.8 kg N ha^{-1}). However, a significant average decrease of 51.1% (from 248.2 kg N ha^{-1} in 2006 to 121.4 kg N ha^{-1} in 2008) was observed over the years. Values in COM1 and COM2 were stable across the years and significantly lower than in CONV and MT, with a three-year average reduction in N uptake of 72.5% as compared to CONV. N uptake was not significantly influenced by the compost application rate. In 2006, COM1 and COM2 took up significantly less N (−70.2%) than 0 N.

At TO, no difference was found between conventional and minimum tillage (three-year average of 233.4 kg N ha^{-1}). However, N uptake in CONV was lower in the second and third year while MT decreased only in the third year. N uptake with compost treatment was not significantly different from that with urea.

In 2009, when all plots were unfertilized to evaluate residual soil fertility related to the previous treatments, no difference in total biomass (on average 23.1 Mg ha^{-1} at TO and 6.9 Mg ha^{-1} at NA) or N uptake (on average 199.9 kg N ha^{-1} at TO and 42.6 kg N ha^{-1} at NA) was found among tillage intensities and N sources (Table 5). However, at TO, COM2 was the only treatment with total biomass production and N uptake significantly higher than 0 N. Maize yields and N uptake in 2009 were, on average, equal to those of the previous years at TO (except 2008 in which yield was affected by hail injuries) while at NA, the tendency to decrease in the first three years was confirmed in 2009 (−57.2% and −49.8% compared to 2008, for yield and N uptake respectively).

3.2 Soil nitrate-N evolution

Soil nitrate-N (SN) content in the 0–60 cm layer (Table 6) during 2006–2008 was significantly higher (P(F) = 0.006) at NA than at TO, with values of the three-year average nearly two times higher (71.0 and 36.4 kg NO_3^{-}–N ha^{-1}, respectively).

In terms of treatment effects at NA, a reduced SN in COM1 was evident only at pre-seeding (Table 6); no treatment differences were found at flowering or harvest. At TO, both pre-seeding and harvest SN was unaffected by treatment. However, at flowering, SN values in CONV and MT were on average 6.8 and 4.2 times higher than compost-fertilized and not fertilized treatments (average value), respectively. Furthermore, we detected no significant effect from compost dosing or from tillage methods. On the other hand, higher precipitation caused SN to be almost three times lower (significant) in 2008 than in 2006 and 2007 (Table 6).

In 2009, no SN difference was detected among the treatments during any crop stage at either site (data not shown). Soil nitrate content at TO was very low (average value across the growing season was 9.3 kg NO_3^{-}–N ha^{-1}) and about the same as rainy 2008 (16.1 kg N ha^{-1}). At NA, SN (58.1 kg NO_3^{-}–N ha^{-1}) was 80.8% of the average of the previous year.

3.3 Short-term soil organic matter evolution

Soil C and N data are presented in Table 7 as the difference between final (2008) and initial (2006) content. These variations represent a short-term soil response to C sequestering strategies and highlight the start of a system trend moving toward a new equilibrium. The SOC variation was more pronounced at NA than at TO. Treatments significantly affected the evolution of soil organic C at both locations and total N at NA. The efficacy of compost and minimum tillage to increase soil C to a greater extent than CONV differed between the sites (Table 7). On average, NA fertilized treatments increased (P(F) = 0.000) consistently in SOC content 2.2 times more than the average absolute variation at TO (0.888 versus 0.400 g C kg^{-1} soil over the three-year period, respectively).

At NA, soil organic C content variation in the 0–30 cm layer was 1.240 g C kg−1 higher in MT than in CONV. The C increase due to COM2 was significantly higher than 0 N, but the difference from CONV was not statistically significant. Based on soil bulk density measured at the beginning and at the end of the 2006–2008 period, organic C concentration variation corresponded to a three year increase of about 4.7 Mg C ha−1 for MT and a three-year increase of 3.75 Mg C ha−1 for COM2, with a confidence interval (c.i.) ranging from 2.6 to 6.9 Mg C ha−1 and 1.6 to 5.8 Mg C ha−1, respectively. At TO, the SOC increase in COM2 was significantly higher than in CONV, MT, and 0 N, which corresponded to an absolute increase of 4.4 Mg C ha−1 (c.i. from 2.7 to 6.1 Mg C ha−1) after three years.

Soil total N variation was not significantly different between the sites. At TO, no treatment effect was observed. At NA, both compost levels increased total N concentration about 0.150 g N kg−1 more than for CONV (+18.5% with respect to CONV in 2008).

4. Discussion

4.1 Soil fertility in experimental sites

Soil chemical and physical properties were the key factors controlling the different responses of maize to treatments at the two study sites. Three elements indicated that the ability of the two soils to sustain crop development differed. First, crop production and N uptake in CONV were always lower at NA than at TO. In spite of N fertilization below crop requirements at TO, crop production remained almost constant across the years (excluding 2008 in which hail damage reduced maize yield) — even in non-fertilized 2009. Using CONV as a reference, its total yield was reduced only by 5.5% in non-fertilized 2009 as compared to 2006. Conversely, at NA, crop production in CONV declined between 2006 and 2008, and finally collapsed in 2009, which made evident that the two soils had different N-supplying potentials.

The second element was soil N availability. The soil N supply potential was estimated by Available N (AvN), calculated as N uptake plus soil mineral-N (SMN) variation between crop sowing and harvest (SMN at harvest − SMN at sowing) (Meisinger, 1984; Bhogal et al., 1999; Montemurro et al., 2006; Alluvione et al., 2008; Fiorentino et al., 2009). AvN represents the potential mineralization of soil organic N (PON) only in the non-fertilized plots; however, it also includes N from fertilizers and the priming effect in the fertilized plots. The differences in N gaseous losses and leaching (Salmerón et al., 2011) among treatments were assumed irrelevant on AvN. Similarly, the contribution of atmospheric N deposition and N from irrigation water was assumed to be the same in all treatments, and therefore not considered in the AvN calculation. At TO, PON was 39.2% higher (143.8 kg N ha−1) than at NA (103.3 kg N ha−1). This was sufficient to sustain plant growth and N uptake of 0 N and yielded a biomass amount no different from the urea-fertilized plots. On average, PON was 61.0% of N uptake in CONV at TO and 55.9% at NA. The higher PON values at TO might have buffered both the urea and compost effect on maize yields as shown by Erhart et al. (2005) and Montemurro et al. (2006).

Last, the third element that confirmed higher microbial activity and soil fertility at TO versus NA was based on a survey of the soil microbial communities at the respective sites (Ventorino et al., 2012). Another study on the same experimental plots (Chiurazzi, 2008), showed fewer non-symbiotic, N-fixing microorganisms at TO relative to NA that might relate to its higher N availability.

Despite this evidence, a higher soil nitrate-N content was detected at NA than at TO, both during the 2006–2008 period and in 2009. Lower average SN at TO might have been the result of higher winter leaching facilitated by its coarser texture (preseeding) and a higher maize N uptake (flowering and harvest) rate. Nevertheless, two results make clear that SN is not a good indicator of N availability or of treatment effect on soil fertility and crop yield. First, although the highest soil nitric-N content existed at NA, maize growth and N uptake were lower there than at TO. Second, maize yield and N uptake were different among NA treatments even though SN was homogeneous across the plots during the cropping season. The opposite occurred at TO, where SN was lower in compost and 0 N, but N uptake did not vary.

The apparent unreliability of SN to indicate soil N fertility may be due to the fact that soil nitrate-N content is the net balance between N availability from several sources and crop uptake, plus N losses. At TO, the high plant available N fulfilled the N needs of maize and did not allow the treatments to effectively influence crop development during the four experimental years. Thus, the higher SN that we found in urea relative to compost and 0 N was due to residual N not taken up by the crop. A series of events confirmed that SOM mineralization compensated for sub-optimal nutrition and that excess SN accumulated in the soil: (i) the absence of a maize response to N fertilization through the experiment, (ii) N uptake levels close to potential for the specific pedo-climate conditions found by Zavattaro et al. (2012) at that site, and (iii) maize yields and N uptake in 2009 were close to 2007 levels despite a lower SN content. Thus, as Monaco et al. (2010) found in an adjacent field experiment, while N fertilization did not influence maize yields in the application year, it is necessary for long-term soil fertility.

At NA, N mineralization from the native soil organic reservoir was tighter and not sufficient to sustain maize growth, thus all available N was taken up by the crop and no residual SN accumulated in the urea treatments compared to 0 N. The lower native N availability at NA versus TO, and the consequent fundamental importance of annual fertilization was reflected in crop production and N uptake when 0 N fell below the urea-fertilized treatments after the first year, as the soil was already unable to sustain maize nutritional needs without external N inputs.

The lower N availability at NA might relate to the ability of the soil to protect organic C from microbial decomposition, thus reducing the N mineralization rate also. As showed by Ventorino et al. (2012) at TO, fungi and cellulosolytic bacteria were positively affected by COM2 due to the simultaneous availability of added organic C and N from SOM. Conversely at NA, repeated compost additions depressed these same microbial populations with respect to urea-fertilized plots. The hydrophobic protection of humified OM added with compost (see Section 4.3) and the soil physical protection on both the added and native organic matter likely reduced C and N availability to microbes, thereby reducing their activity at NA site. The latter hypothesis is supported by water stable aggregate measurements by Spaccini and Piccolo (2012) on NA and TO soils during the same trial, who showed that the average aggregate MWD (Mean Weight Diameter) for NA soil was twice that of TO soil (1.4 versus 0.7). The same author reported that at NA, 37% and 34% of total aggregates was included in the 4.75–1.00 and 1.00–0.50 mm diameter ranges, respectively, while TO soil showed values of 12% and 25% for these same aggregate classes, respectively. Since SOM content is lower at NA than at TO site (7.2 g kg−1 versus 10.2 g kg−1, respectively) the higher clay content could be considered the key factor controlling the macro aggregation in NA soil, allowing a higher physical protection of SOM.

Lower N availability at the NA site could have also been favored by a lower oxygen availability in the soil, as suggested by a threefold higher NH4 +:NO3 − ratio (Alluvione et al., 2008), higher soil bulk density, and finer soil texture. The lower oxygen availability might have hindered organic matter mineralization, N availability, root development, and finally, maize growth.

4.2 Minimum tillage

Adoption of minimum tillage produced the same maize yields, N uptake, and soil nitrate-N levels at both locations as did traditional plowing, with the advantage that crop yield and N uptake were even more stable across years. Specifically, the maize yield variation coefficients in the three years were lower for MT as compared to CONV (13.1% versus 15.2% respectively at NA and 10.7% versus 13.6% respectively at TO). Our results agreed with other research and indicated that MT is a viable alternative to traditional deep plowing (Alluvione et al., 2011), especially in Mediterranean climates (Pala et al., 2008).

Reduction of tillage intensity was also effective in increasing persistence of C derived from crop residues at NA, which is likely because maize residue decomposition by soil microbes was mitigated by the protection effect of clay minerals. Soil C measurements showed a three-year increase of 4.7 Mg C ha−1 for MT, with 2.7 Mg C ha−1 to 6.9 Mg ha−1 as lower and upper limits of the confidence interval. Such increase is quite high compared to our forecasted results, so a partial short-term C balance was arranged to validate it. A rough estimate of biomass input from MT maize roots done using belowground measurements from 2008 (data not shown) showed an average value of 3.7 Mg d.m. ha−1, which corresponded to a root:shoot ratio of 0.22 kg kg−1. The first two year belowground biomass production was estimated using this coefficient and resulted in 4.85 (2006) and 4.45 Mg ha−1 (2007). Therefore, C root input to the soil was 5.21 Mg C ha−1 in three years according to a C content of 0.40 kg kg−1 (Whipps, 1990).

Another significant contribution to measured organic C is represented by extra root-derived C (exudates and turnover) that Swinnen et al. (1995) suggest can be estimated as 10% of net C assimilation. In this case, it corresponds to a total of 3.2 Mg C ha−1 over the three-year period. In this way, we can hypothesize that the total C input of 8.4 Mg C ha−1 raised the measured organic C at least 2.7 Mg C ha−1 (32% efficiency); this result seems realistic since our measures included both organic C from stabilized organic matter and not yet decomposed crop residues. Moreover, high and fast C sequestration (Freibauer et al., 2004) and low residue mineralization (Thomsen et al., 1996) are common to clay soils.

At TO, MT was a less effective for increasing soil organic C even though C input from roots and exudates, calculated as a percentage of crop yields, were higher than at NA (data not shown). This result was due the low C-protecting attitude of the soil that favored crop residue oxidation from soil microbiota. Still, it is possible that C sequestration at TO might occur in the medium- to long-term and that absence of a treatment effect after three years is due to a slow initial C accumulation rate (West and Post, 2002; Alvarez, 2005).

4.3 Compost fertilization

Compost is known to release a small portion (about 10% on average) of its total N in the first months after soil incorporation (Iglesias-Jimenez and Alvarez, 1993; Amlinger et al., 2003; Nevens and Reheul, 2003; Pansu and Thuriès, 2003; Hargreaves et al., 2008; Diacono and Montemurro, 2010), since labile N is only a small portion of total N (Beraud et al., 2005).

As already discussed, the high native N soil available at TO masked low compost mineralization as observed by Erhart et al. (2005) and Montemurro et al. (2006). Low N availability from compost was made evident by several study events: lower maize yield and N uptake tendency compared to urea fertilization; significantly lower SN content at flowering than urea; no difference in SN content versus 0 N; absence of compost dose effect. In addition, gaseous CO2 and N2O emissions monitored by Alluvione et al. (2010) on the same plots confirmed the low compost mineralization. From these events, we hypothesize that a slow N release occurred from compost since both SN and N uptake were always higher than in 0 N plots; however, the increases were not significant due to the combined effect of compost distribution and mineralization rates. In fact, such a release would have been hard to detect given the distributed rates of 130 or 260 kg N ha−1 of compost that resulted in N uptake increases below the LSD that we found among treatments (56.1 kg N ha−1; see Table 4). A 15N study performed at the same site confirmed a low release (20% in the 1st year) of N from compost (Celano et al., 2012).

Contrary to TO results, those from NA were consistent with Eriksen et al. (1999) and Hargreaves et al. (2008), who showed that compost fertilization reduced maize development and N uptake in soils with low N availability. Indeed, maize development and N uptake were reduced even below that of 0 N in the first year, which suggested that the lack of N limiting maize growth was probably due to the humified OM added with compost that was able to preserve native SOM from degradation, building large hydrophobic domains (Spaccini et al., 2002) and reducing the organic matter available to microbes. This effect could have been particularly emphasized by soil properties at NA site, mainly its low OC content and the clay mediated SOC physical protection while no effect was detected at TO site due to the different pedological conditions (lower clay and higher OC content). A comparison of our results with field research from Fagnano et al. (2011) confirmed that the agronomic performance of compost is affected mainly by soil conditions rather than by climate. In fact, on sandy-loam soil close to NA, they found compost from municipal solid wastes (MSW) positively affected lettuce yields, as we observed at TO. No reduction in N availability with an increased compost rate was observed at NA, probably because the COM1 dose was sufficient to achieve the maximum hydrophobic protection. In fact, maize yields in compost plots remained constant throughout the experiment while other treatments, 0 N included, progressively reduced their performances to levels consistent with the compost-treated plot. No compost-dose effect was evident on SN given that maize had already exploited all available N, as previously noted in the discussion of soil fertility differences.

Aside from the observed negative effect of compost application on plant N availability in the SOC-protecting soil at NA, high N availability is possible in the long-term. In fact, repeated compost application can progressively increase the N mineralized from added organic N (Leroy et al., 2007), and result in an N availability similar to one provided by mineral fertilizers (Erhart et al., 2005). Our results suggest that compost application is suitable for maize fertilization only in fertile and low clay soils, as found at TO, where the lower protection ability of the soil promotes native SOM and compost mineralization and overcomes its low N release. In instances where compost fertilization might reduce yields, compost integration with mineral fertilizers might be the best solution (Montemurro et al., 2006), at least until the release from accumulated organic N were sufficient (Diacono and Montemurro, 2010). A compost plus mineral-N fertilization strategy could also be a viable option from an environmental perspective, reducing the potential risk of pollution of adjacent ecosystems due to macro and micronutrients excesses in the soil. In fact, compost rate calibration for crop N needs may inadvertently apply excess P and K, trace elements, and metals (Hargreaves et al., 2008; Diacono and Montemurro, 2010). Applying compost at a rate equal to N uptake in CONV during 2006 in each year would have caused distribution, on average, in excess of 8.8 kg P ha^{-1} and 56.0 kg K ha^{-1} at TO, and 5.7 kg P ha^{-1} and 22.4 kg K ha^{-1} at NA).

In accordance with the results of many researchers (e.g. Diacono and Montemurro, 2010), we found that compost increased SOC. If SOC in CONV is considered as a reference, then the adoption of COM2 at TO would have retained 55.1% of added compost C into the soil. We assumed that the calculated C increase was determined by compost C input alone, as no difference in aboveground biomass production between COM2 and CONV occurred. Consequently, we also assumed that a similar development in root biomass took place (Alluvione et al., 2009). This percentage was similar to the C storage result in a long-term field experiment located at the same TO site for a different stable organic fertilizer such as manure. In fact, after the first year from field application, 46% of farmyard manure- C was still in the soil. Conversely, on the same long-term platform, increasing amounts of urea did not produce any significant SOM content differences, which indicated that the amount of mineral- N supplied was not decisive for C sequestration (Bertora et al., 2009). At NA, similar to TO, SOC concentration in COM2 was also almost higher than in CONV, thus suggesting that C storage could be achieved in the long-term if compost were repeatedly applied. An in-depth examination of compost effects on the molecular changes in SOC has confirmed the formation of more stable C compounds, such as fatty acids, n-alkanes, and various biopolyester derivatives (Spaccini et al., 2009).

5. Conclusions

Alternative and C-friendly strategies need evaluation to optimize the best practice for crop yield and SOC sequestration in the specific pedo-climate of different agro-ecosystems. We conclude that the tested techniques are ideal options to substitute for traditional management in specific soil conditions. Application of a stable organic matter such as compost is valuable in soils with a low attitude to SOC physical protection, but should be avoided in soils characterized by high clay content. Even though soil C sequestration is achievable under both conditions, crop yields can be depleted in soils where the low availability of SOM to microbes also entails a reduced N availability. In fact, crop production can be sustained, despite low compost N mineralization rates, in soils with high native N availability. When such conditions exist, coupling compost application with a mineral-N source is necessary to compensate for the low N release and also helps to balance nutrients other than N. On the other hand, compost applied to SOC-protecting soils can reduce N availability and depress crop development. Of course, after long-term (decades) compost fertilization, even these soils may be improved in both chemical (N availability from SOM mineralization) and physical fertility (aeration after macro-porosity increase) to reach their capacity to sustain crop N requirements.

Preservation of organic matter oxidation through minimum tillage maintained crop production in soils with both high and low clay content, but its fit is better in soils where SOC-protection is higher. Under such conditions, SOC increases are best pursued by reducing soil disturbance to hinder C mineralization, rather than by adding stable organic matter. Organic matter addition is less effective because plowing to incorporate it causes excessive aeration. On the other hand, in low clay soils, aeration is high and tillage intensity reduction is insufficient to hinder residue mineralization, which explains why the addition of stable compost increased soil organic C only at TO. Our findings confirm that no single solution to environmental issues exists; instead, a series of options that require evaluation for each unique combination of pedo-climate and farming system conditions are necessary.

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References

Abiven, S., Menasseri, S., Chenu, C., 2009. The effects of organic inputs over time on soil aggregate stability - A literature analysis. Soil Biol. Biochem. 41, 1-12.

Allen, R., Pereira, L., Raes, D., Smith, M., 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper no. 56, Rome.

Alluvione, F., Fagnano, M., Fiorentino, N., Grignani, C., Quaglietta Chiarandà, F., Zavattaro, L., 2008. Maize Response to Repeated Compost Additions in Two Contrasting Environments in Italy. Ita. J. Agron. 3, 171-172.

Alluvione, F., Halvorson, A.D., Del Grosso, S.J., 2009. Nitrogen, tillage, and crop rotation effects on carbon dioxide and methane fluxes from irrigated cropping systems. J. Environ. Qual. 38, 2023-2033.

Alluvione, F., Bertora, C., Zavattaro, L., Grignani, C., 2010. Nitrous Oxide and Carbon Dioxide Emissions Following Green Manure and Compost Fertilization in Corn. Soil Sci. Soc. Am. J. 74, 384-395.

Alluvione, F., Moretti, B., Sacco, D., Grignani, C., 2011. EUE (energy use efficiency) of cropping systems for a sustainable agriculture. Energy 36, 4468-4481.

Alvarez, R., 2005. A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage. Soil Use Manage. 21, 38-52.

Amlinger, F., Götz, B., Dreher, P., Geszti, J., Weissteiner, C., 2003. Nitrogen in biowaste and yard waste compost: dynamics of mobilisation and availability- a review. Eur. J. Soil Biol. 39, 107-116.

Astori, C., 1998. Fitotossicità, in: Genevini, P.L. (Ed.), Compost e agricoltura. Fondazione Lombardia per l'Ambiente, Milano, pp. 185-202.

Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J., 2007. Tillage and soil carbon sequestration-What do we really know? Agr. Ecosyst. Environ. 118, 1-5.

Bauer, A., Black, A.L., 1994. Quantification of the effect of soil organic matter content on soil productivity. Soil Sci. Soc. Am. J. 58, 185-193.

Beraud, J., Fine, P., Yermiyahu, U., Keinan, M., Rosenberg, R., Hadas, A., Bar-Tal, A., 2005. Modeling Carbon and Nitrogen Transformations for Adjustment of Compost Application with Nitrogen Uptake by Wheat. J. Environ. Qual. 34, 664-675.

Bernal, M.P., Sánchez-Monedero, M.A., Paredes, C., Roig, A., 1998. Carbon mineralization from organic wastes at different composting stages during their incubation with soil. Agr. Ecosyst. Environ. 69, 175-189.

Bertora, C., Zavattaro, L., Sacco, D., Monaco, S., Grignani, C., 2009. Soil organic matter dynamics and losses in manured maize-based forage systems. Eur. J. Agron. 30, 177-186.

Bhogal, A., Hatch, D.J., Shepherd, M.A., Jarvis, S.C., 1999. Comparison of methodologies for field measurement of net nitrogen mineralisation in arable soils. Plant Soil 207, 15-28.

Bot, A., Benites, J., 2005. The importance of soil organic matter. FAO Soils Bulletin 80. Food and Agriculture Organization of The United Nations, Rome.

Bowden, C., Spargo, J., Evanylo, G., 2007. Mineralization and N fertilizer equivalent value of compost as assessed by tall fescue (Festuca arundinacea). Compost Sci. Util. 15, 111-118.

Brinton, W.F., 2000. Compost quality standards and guidelines: an international view. In: Inc., W.a.r.l. (Ed.). http://www.woodsend.org/pdf-files/nysar-ne.pdf.

Brown, L.R., 1984. State of the World 1984: A Worldwatch Institute Report on Progress Toward a Sustainable Society Worldwatch Institute.

Bruce, J.P., Frome, M., Haites, E., Janzen, H., Lal, R., Paustian, K., 1999. Carbon sequestration in soils. J. Soil Water Conserv. 54, 382-389.

Celano, G., Alluvione, F., Ali Mohamed, M.A.A., Spaccini, R., 2012. The stable isotopes approach to study C and N sequestration processes in a plant-soil system, in: Piccolo, A. (Ed.), Carbon sequestration in agricultural soils. A multidisciplinary approach to innovative methods. Springer-Verlag, Berlin Heidelberg, pp. 107-144.

Celik, I., 2005. Land-use effects on organic matter and physical properties of soil in a southern Mediterranean highland of Turkey. Soil Till. Res. 83, 270-277.

Chefetz, B., Hatcher, P.G., Hadar, Y., Chen, Y., 1996. Chemical and Biological Characterization of Organic Matter during Composting of Municipal Solid Waste. J. Environ. Qual. 25, 776-785.

Chiurazzi, M., 2008. Microbial diversity as soil quality indicator in agricultural soils. PhD thesis, University of Naples Federico II, pp 24-40.

Chukwujindu, M.A.I., Egun , A.C., Emuh, F.N., Isirimah, N.O., 2006. Compost Maturity Evaluation and its Significance to Agriculture. Pak. J. Bio. Sci. 9, 2933-2944.

Claassen, V.P., Carey, J.L., 2004. Regeneration of nitrogen fertility in disturbed soils using compost. Compost Sci. Util. 12, 145-152.

Courtney, R.G., Mullen, G.J., 2008. Soil quality and barley growth as influenced by the land application of two compost types. Bioresource Technol. 99, 2913-2918.

Dam, R.F., Mehdi, B.B., Burgess, M.S.E., Madramootoo, C.A., Mehuys, G.R., Callum, I.R., 2005. Soil bulk density and crop yield under eleven consecutive years of corn with different tillage and residue practices in a sandy loam soil in central Canada. Soil Till. Res. 84, 41-53.

Diacono, M., Montemurro, F., 2010. Long-term effects of organic amendments on soil fertility. A review. Agron. Sustain. Dev. 30, 401-422.

Dick, W.A., Gregorich, E.G., 2004. Developing and maintaining soil organic matter levels, in: Schjonning, P., Elmholt, S., Christensen, B.T. (Eds.), Managing soil quality challenges in modern agriculture. CABI Publishing, Wallingford, Oxon, pp. 103-120.

Doran, J.W., Parking, T.B., 1994. Defining and assessing soil quality, in: Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A. (Eds.), Defining Soil Quality for a Sustainable Environment. SSSA, Madison, WI, pp. 3-21.

Düring, R.A., Gäth, S., 2002. Utilization of municipal organic wastes in agriculture: where do we stand, where will we go? J. Plant Nutr. Soil Sc. 165, 544-556.

Erhart, E., Hartl, W., Putz, B., 2005. Biowaste compost affects yield, nitrogen supply during the vegetation period and crop quality of agricultural crops. Eur. J. Agron. 23, 305-314.

Erhart, E., Feichtinger, F., Hartl, W., 2007. Nitrogen leaching losses under crops fertilized with biowaste compost compared with mineral fertilization. J. Plant Nutr. Soil Sc.170, 608-614.

Eriksen, G.N., Coale, F.J., Bollero, G.A., 1999. Soil nitrogen dynamics and maize production in municipal solid waste amended soil. Agron. J. 91, 1009-1016.

Eswaran, H., Van Den Berg, E., Reich, P., 1993. Organic Carbon in Soils of the World. Soil Sci. Soc. Am. J. 57, 192-194.

European Commission, 2000. Success stories on composting and separate collection. Directorate General for the Environment, European Commission, Brusselles.

European Community, 2009. Council Regulation (EC) No 74/2009 of 19 January 2009 amending Regulation (EC) No 1698/2005 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD). Official journal of the European Union, pp. 100-110.

European Council, 2005. Council Regulation (EC) No 1698/2005 of 20 September 2005 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD). Official journal of the European Union, pp. 1-40.

Fagnano, M., Quaglietta Chiarandà, F., 2008. Environmental Effect of Soil Tillage, in: Formato, A. (Ed.), Advances in Soil & Tillage Research. Transworld Research Network, Kerala - India, pp. 203-217.

Fagnano, M., Adamo, P., Zampella, M., Fiorentino, N., 2011. Environmental and agronomic impact of fertilization with composted organic fraction from municipal solid waste. Agr. Ecosyst. Environ. 141, 100-107.

Fiorentino, N., Fagnano, M., Quaglietta Chiarandà, F., 2009. Nitrogen management in a Mediterranean cropping system: the role of green manure, in: Grignani, C., Acutis, M., Zavattaro, L., Bechini, L., Bertora, C., Marino Gallina, P., Sacco, D. (Eds.), Proceedings of the 16th Nitrogen workshop - Connecting different scales of N use in agriculture, Turin, Italy, pp. 407-408.

Follett, R.F., 2001. Soil management concepts and carbon sequestration in cropland soils. Soil Till. Res. 61, 77-92.

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

Gigliotti, G., Businelli, D., Giusquiani, P.L., 1996. Trace metals uptake and distribution in corn plants grown on a 6-year urban waste compost amended soil. Agr. Ecosyst. Environ. 58, 199-206.

Ginting, D., Kessavalou, A., Eghball, B., Doran, J.W., 2003. Greenhouse Gas Emissions and Soil Indicators Four Years after Manure and Compost Applications. J. Environ. Qual. 32, 23-32.

Grignani, C., Zavattaro, L., Sacco, D., Monaco, S., 2007. Production, nitrogen and carbon balance of maize-based forage systems. Eur. J. Agron. 26, 442-453.

Grignani, C., Alluvione, F., Bertora, C., Zavattaro, L., Fagnano, M., Fiorentino, N., Quaglietta Chiarandà, F., Amato, M., Lupo, F., Bochicchio, R., 2012. Field plots and crop yields under innovative methods of carbon sequestration in soil, in: Piccolo, A. (Ed.), Carbon sequestration in agricultural soils. A multidisciplinary approach to innovative methods. Springer-Verlag, Berlin Heidelberg, pp. 39-60.

Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biol. 8, 345-360.

Halvorson, A.D., Reule, C.A., Follett, R.F., 1999. Nitrogen fertilization effects on soil carbon and nitrogen in a dryland cropping system. Soil Sci. Soc. Am. J. 63, 912-917.

Hargreaves, G., Samani, Z., 1985. Reference crop evapotranspiration from temperature. Appl. Eng. Agric. 1, 96-99.

Hargreaves, J.C., Adl, M.S., Warman, P.R., 2008. A review of the use of composted municipal solid waste in agriculture. Agr. Ecosyst. Environ. 123, 1-14.

Hernanz, J.L., Sánchez-Girón, V., Navarrete, L., 2009. Soil carbon sequestration and stratification in a cereal/leguminous crop rotation with three tillage systems in semiarid conditions. Agr. Ecosyst. Environ. 133, 114-122.

Holland, J.M., 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agr. Ecosyst. Environ. 103, 1-25.

Hutchinson, J.J., Campbell, C.A., Desjardins, R.L., 2007. Some perspectives on carbon sequestration in agriculture. Agr. Forest Meteor. 142, 288-302.

Iglesias-Jimenez, E., Alvarez, C.E., 1993. Apparent Availability of Nitrogen in Composted Municipal Refuse. Biol. Fert. Soils 16, 313-318.

Ikumo, H., 2005. Estimation of potential supply of livestock waste compost to replace chemical fertilizer use in Japan based on 2000 Census of Agriculture. Jpn. Agric. Res. Q. 39, 83-89.

IPCC, 2007a. 2006 IPCC guidelines for national greenhouse gas inventories - Volume 4: Agriculture, forestry and other land use. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.htm.

IPCC, 2007b. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paolo, Delhi.

Johnston, A.E., 1991. Soil fertility and soil organic matter. In: Wilson, W.S. (Ed.), Advances in soil organic matter research: The impact on agriculture and the environment Royal Society of Chemistry, Cambridge, pp. 299-313.

Jordão, C., Cecon, P., Pereira, J., 2003. Evaluation of metal concentrations in edible vegetables grown in compost amended soil. International Journal of Environmental Studies 60, 547-562.

JRC, 2001. European Soil Database (online database available at: http://eusoils.jrc.ec.europa.eu/library/Data/EFSA/). European Commission – DG JRC

Lal, R., Kimble, J.M., 1997. Conservation tillage for carbon sequestration. Nutr. Cycl. Agroecosys. 49, 243-253.

Lal, R., 2004. Agricultural activities and the global carbon cycle. Nutr. Cycl. Agroecosys. 70, 103-116.

Lal, R., 2008. Soils and sustainable agriculture. A review. Agron. Sustain. Dev. 28, 57-64.

Lal, R., 2009. Challenges and opportunities in soil organic matter research. Eur. J. Soil Sci. 60, 158-169.

Lal, R., 2011. Sequestering carbon in soils of agro-ecosystems. Food Policy 36, Supplement 1, S33-S39.

Leroy, B.L.M.M., Bommele, L., Reheul, D., Moens, M., De Neve, S., 2007. The application of vegetable, fruit and garden waste (VFG) compost in addition to cattle slurry in a silage maize monoculture: Effects on soil fauna and yield. Eur. J. Soil Biol. 43, 91-100.

López-Fando, C., Pardo, M.T., 2011. Soil carbon storage and stratification under different tillage systems in a semi-arid region. Soil Till. Res. 111, 224-230.

Luo, Z., Wang, E., Sun, O.J., 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agr Ecosyst. Environ. 139, 224-231.

Lynch, D.H., Voroney, R.P., Warman, P.R., 2006. Use of 13C and 15N natural abundance techniques to characterize carbon and nitrogen dynamics in composting and in compost-amended soils. Soil Biol. Biochem. 38, 103-114.

Manlay, R.J., Feller, C., Swift, M.J., 2007. Historical evolution of soil organic matter concepts and their relationships with the fertility and sustainability of cropping systems. Agr Ecosyst. Environ. 119, 217-233.

Mazzoncini, M., Sapkota, T.B., Bàrberi, P., Antichi, D., Risaliti, R., 2011. Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. Soil Till. Res. 114, 165-174.

Meisinger, J.J., 1984. Evaluating plant available nitrogen in soil crop systems, in: Hauch, R. (Ed.), Nitrogen in crop production, Madison, pp. 391-416.

Melero, S., Madejón, E., Ruiz, J.C., Herencia, J.F., 2007. Chemical and biochemical properties of a clay soil under dryland agriculture system as affected by organic fertilization. Eur. J. Agron. 26, 327-334.

Monaco, S., Sacco, D., Borda, T., Grignani, C., 2010. Field measurement of net nitrogen mineralization of manured soil cropped to maize. Biol. Fert. Soils 46, 179-184.

Mondini, C., Sequi, P., 2008. Implication of soil C sequestration on sustainable agriculture and environment. Waste Manage. 28, 678-684.

Montemurro, F., Maiorana, M., Ferri, D., Convertini, G., 2006. Nitrogen indicators, uptake and utilization efficiency in a maize and barley rotation cropped at different levels and sources of N fertilization. Field Crop. Res. 99, 114-124.

Moreno, J.L., García, C., Hernández, T., Pascual, J.A., 1996. Transference of heavy metals from a calcareous soil amended with sewage-sludge compost to barley plants. Bioresource Technol. 55, 251-258.

Morris, N.L., Miller, P.C.H., J.H.Orson, Froud-Williams, R.J., 2010. The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment-A review. Soil Till. Res. 108, 1-15.

Nevens, F., Reheul, D., 2003. The application of vegetable, fruit and garden waste (VFG) compost in addition to cattle slurry in a silage maize monoculture: nitrogen availability and use. Eur. J. Agron. 19, 189-203.

Pala, M., Ryan, J., Diekmann, J., Singh, M., 2008. Barley and vetch yields from dryland rotations with varying tillage and residue management under Mediterranean conditions. Exp. Agr. 44, 559-570.

Pansu, M., Thuriès, L., 2003. Kinetics of C and N mineralization, N immobilization and N volatilization of organic inputs in soil. Soil Biol. Biochem. 35, 37-48.

Paustian, K., Six, J., Elliott, E.T., Hunt, H.W., 2000. Management options for reducing CO2 emissions from agricultural soils. Biogeochemistry 48, 147-163.

Piccolo, A., Spaccini, R., Nieder, R., Richter, J., 2004. Sequestration of a Biologically Labile Organic Carbon in Soils by Humified Organic Matter. Climatic Change 67, 329-343.

Pinheiro, E.F.M., Pereira, M.G., Anjos, L.H.C., 2004. Aggregate distribution and soil organic matter under different tillage systems for vegetable crops in a Red Latosol from Brazil. Soil Till. Res.77, 79-84.

Ryan, J., Ibrikci, H., Sommer, R., McNeill, A., Donald, L.S., 2009. Chapter 2 Nitrogen in Rainfed and Irrigated Cropping Systems in the Mediterranean Region. Adv. Agron. Academic Press, pp. 53-136.

Salmerón, M., Isla, R., Cavero, J., 2011. Effect of winter cover crop species and planting methods on maize yield and N availability under irrigated Mediterranean conditions. Field Crop. Res. 123, 89-99.

Scherr, S.J., Sthapit, S., 2009. Farming and land use to cool the planet, in: Institute, W. (Ed.), 2009 State of the World. Into a warming world.

Silva, M.T.B., Menduina, A.M., Seijo, Y.C., Viqueira, F.D.-F., 2007. Assessment of municipal solid waste compost quality using standardized methods before preparation of plant growth media. Waste Manage. Res. 25, 99-108.

Six, J., Elliott, E.T., Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32, 2099-2103.

Six, J., Feller, C., Denef, K., Ogle, S.M., Sa, J.C.d.M., Albrecht, A., 2002. Soil organic matter, biota and aggregation in temperate and tropical soils - Effects of no-tillage. Agronomie 22, 755-775.

Sombrero, A., de Benito, A., 2010. Carbon accumulation in soil. Ten-year study of conservation tillage and crop rotation in a semi-arid area of Castile-Leon, Spain. Soil Till. Res. 107, 64-70.

Spaccini, R., Piccolo, A., Conte, P., Haberhauer, G., Gerzabek, M.H., 2002. Increased soil organic carbon sequestration through hydrophobic protection by humic substances. Soil Biol. Biochem. 34, 1839-1851.

Spaccini, R., Sannino, D., Piccolo, A., Fagnano, M., 2009. Molecular changes in organic matter of a compost-amended soil. Eur. J. Soil Sci. 60, 287-296.

Spaccini, R., Piccolo, A., 2012. Carbon sequestration in soils by hydrophobic protection and *in-situ* catalyzed photo-polymerization of soil organic matter (SOM). Chemical and physical-chemical aspects of SOM in field plots**,** in: Piccolo, A. (Ed.), Carbon sequestration in agricultural soils. A multidisciplinary approach to innovative methods. Springer-Verlag, Berlin Heidelberg, pp. 61-105.

Strahler, A.N., Strahler, A.H., 1984. Elements of Physical Geography. John Wiley & Sons, New York.

Swinnen J, Vanveen JA and Merckx R., 1995. Carbon fluxes in the rhizosphere of winter wheat and spring barley with conventional vs integrated farming. *Soil Biol Biochem* **27**:811–820.

Tejada, M., Gonzalez, J.L., 2003. Effects of the application of a compost originating from crushed cotton gin residues on wheat yield under dryland conditions. Eur. J. Agron. 19, 357-368.

Thomsen, I.K., Oades, J.M., Amato, M., 1996. Turnover of N-15 in undisturbed root systems and plant materials added to three soils. Soil Biol. Biochem. 28, 1333-1339.

Triberti, L., Nastri, A., Giordani, G., Comellini, F., Baldoni, G., Toderi, G., 2008. Can mineral and organic fertilization help sequestrate carbon dioxide in cropland? Eur. J. Agron. 29, 13-20.

UNFCCC, 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change. In: UNFCCC (Ed.).

Van den Putte, A., Govers, G., Diels, J., Gillijns, K., Demuzere, M., 2010. Assessing the effect of soil tillage on crop growth: A meta-regression analysis on European crop yields under conservation agriculture. Eur. J. Agron. 33, 231-241.

Van Soest, P.J., Robertson, J.B., Lewis, B.A., 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. J. Dairy Sci. 74, 3583-3597.

Ventorino, V., De Marco, A., Pepe, O., Virzo De Santo, A., Moschetti, G., 2012. Impact of innovative agricultural practices of carbon sequestration on soil microbial community, in: Piccolo, A. (Ed.), Carbon sequestration in agricultural soils. A multidisciplinary approach to innovative methods. Springer-Verlag, Berlin Heidelberg, pp. 145-178.

Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 37, 29-38.

West, T.O., Post, W.M., 2002. Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation: A Global Data Analysis. Soil Sci. Soc. Am. J. 66, 1930-1946.

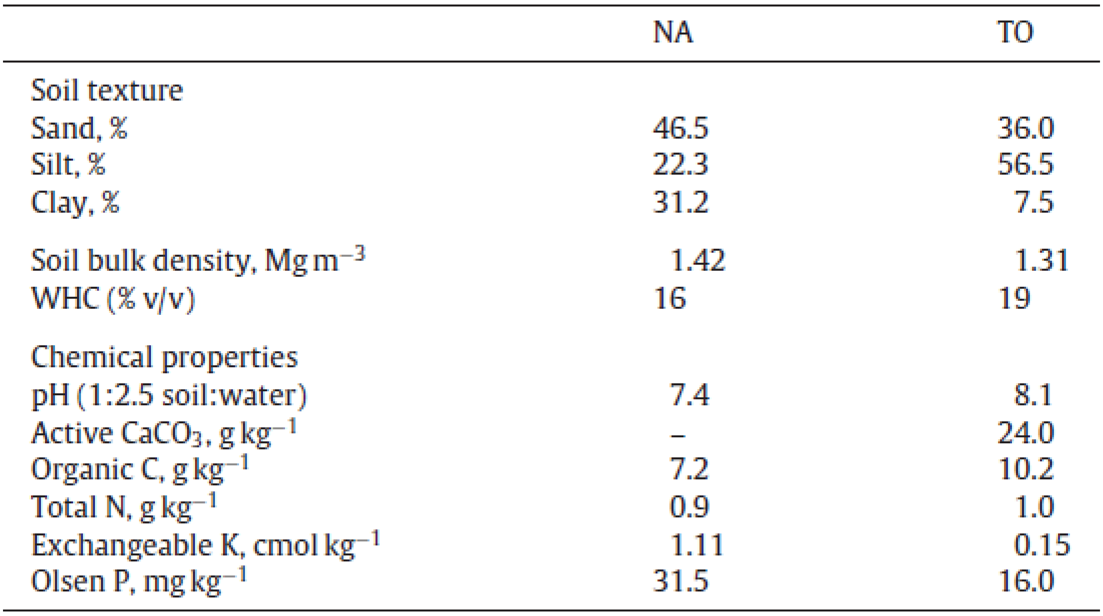
Whipps, J.M., 1990. Carbon economy, in: Lynch, J.M. (Ed.), The Rhizosphere. John Wiley and Sons Ltd., Chichester, England, pp 59-97.

Zavattaro, L., Monaco, S., Sacco, D., Grignani, C., 2012. Options to reduce the N impact of maize in intensive cropping systems. Agr Ecosyst. Environ. 147, 24-35.

Zdruli, P., Jones, R.J.A., Montanarella, L., 2004. Organic Matter in the Soils of Southern Europe. European Soil Bureau Technical Report. Luxembourg.

Table 1

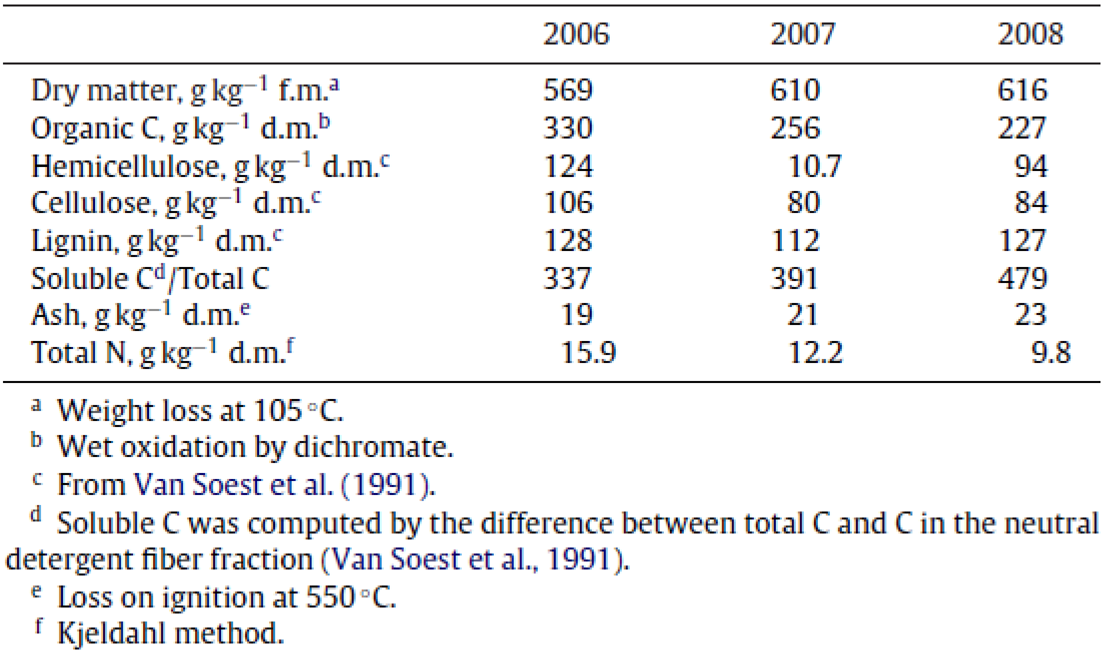
Selected soil chemical and physical properties in the 0- to 30-cm layer (plowed layer) at the study sites.



	NA	TO
Soil texture		
Sand, %	46.5	36.0
Silt, %	22.3	56.5
Clay, %	31.2	7.5
Soil bulk density, Mg m^{-3}	1.42	1.31
WHC (% v/v)	16	19
Chemical properties		
pH (1:2.5 soil:water)	7.4	8.1
Active $CaCO_3$, g kg^{-1}	–	24.0
Organic C, g kg^{-1}	7.2	10.2
Total N, g kg^{-1}	0.9	1.0
Exchangeable K, cmol kg^{-1}	1.11	0.15
Olsen P, mg kg^{-1}	31.5	16.0

Table 2

Chemical composition of the compost added to plots each year.



	2006	2007	2008
Dry matter, g kg^{-1} f.m.[a]	569	610	616
Organic C, g kg^{-1} d.m.[b]	330	256	227
Hemicellulose, g kg^{-1} d.m.[c]	124	10.7	94
Cellulose, g kg^{-1} d.m.[c]	106	80	84
Lignin, g kg^{-1} d.m.[c]	128	112	127
Soluble C[d]/Total C	337	391	479
Ash, g kg^{-1} d.m.[e]	19	21	23
Total N, g kg^{-1} d.m.[f]	15.9	12.2	9.8

[a] Weight loss at 105 °C.

[b] Wet oxidation by dichromate.

[c] From Van Soest et al. (1991).

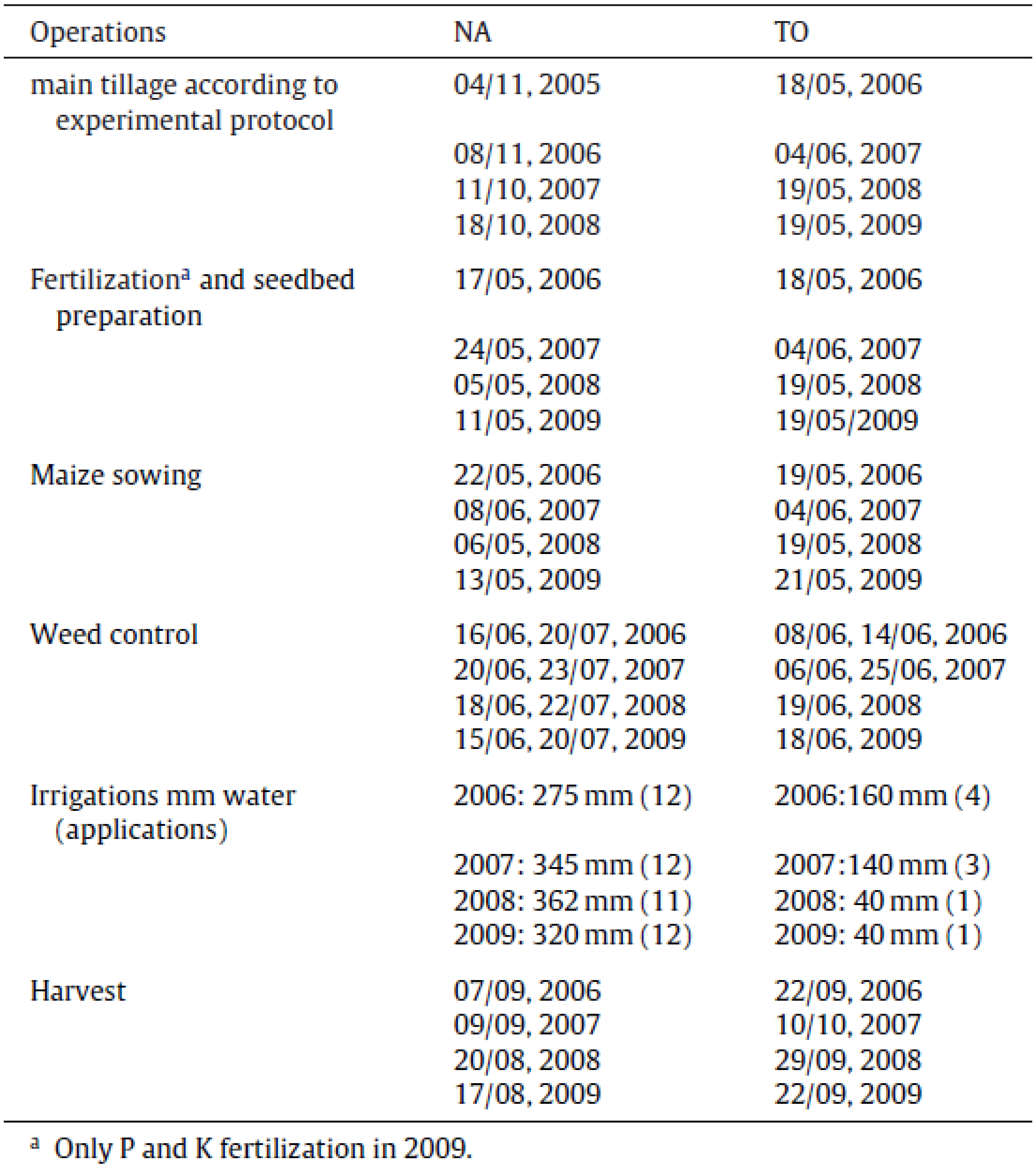
[d] Soluble C was computed by the difference between total C and C in the neutral detergent fiber fraction (Van Soest et al., 1991).

[e] Loss on ignition at 550 °C.

[f] Kjeldahl method.

Table 3

Schedule (day/month) of agronomic operations at the two sites.

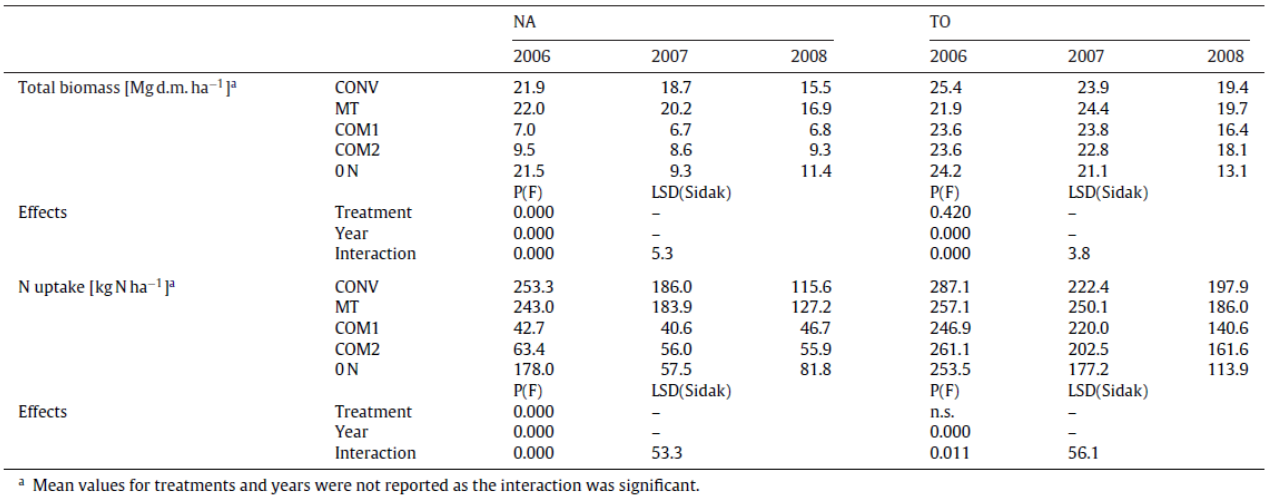


Operations	NA	TO
main tillage according to experimental protocol	04/11, 2005	18/05, 2006
	08/11, 2006	04/06, 2007
	11/10, 2007	19/05, 2008
	18/10, 2008	19/05, 2009
Fertilization[a] and seedbed preparation	17/05, 2006	18/05, 2006
	24/05, 2007	04/06, 2007
	05/05, 2008	19/05, 2008
	11/05, 2009	19/05/2009
Maize sowing	22/05, 2006	19/05, 2006
	08/06, 2007	04/06, 2007
	06/05, 2008	19/05, 2008
	13/05, 2009	21/05, 2009
Weed control	16/06, 20/07, 2006	08/06, 14/06, 2006
	20/06, 23/07, 2007	06/06, 25/06, 2007
	18/06, 22/07, 2008	19/06, 2008
	15/06, 20/07, 2009	18/06, 2009
Irrigations mm water (applications)	2006: 275 mm (12)	2006:160 mm (4)
	2007: 345 mm (12)	2007:140 mm (3)
	2008: 362 mm (11)	2008: 40 mm (1)
	2009: 320 mm (12)	2009: 40 mm (1)
Harvest	07/09, 2006	22/09, 2006
	09/09, 2007	10/10, 2007
	20/08, 2008	29/09, 2008
	17/08, 2009	22/09, 2009

[a] Only P and K fertilization in 2009.

Table 4

Total biomass and N uptake of the different treatments at NA and TO during the three years of treatment application (2006 to 2008). The following were the studied treatments: moldboard plowing after urea fertilization (CONV), minimum tillage after urea fertilization (MT), compost supplied at two levels (COM1 and COM2) followed by moldboard plowing, and non-N-fertilized control plowed by moldboard (0 N).

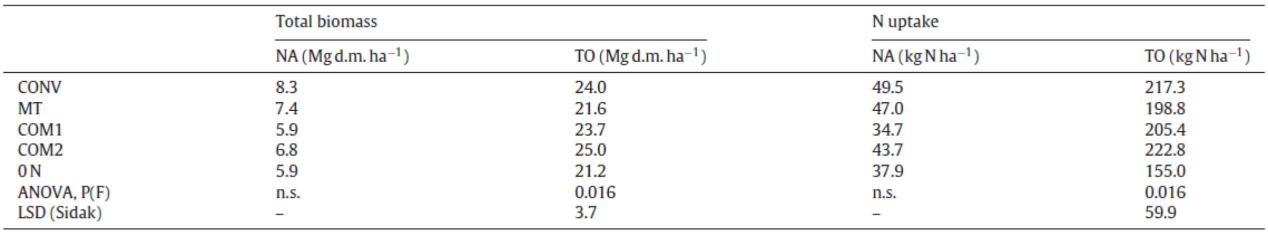


		NA			TO		
		2006	2007	2008	2006	2007	2008
Total biomass [Mg d.m. ha^{-1}][a]	CONV	21.9	18.7	15.5	25.4	23.9	19.4
	MT	22.0	20.2	16.9	21.9	24.4	19.7
	COM1	7.0	6.7	6.8	23.6	23.8	16.4
	COM2	9.5	8.6	9.3	23.6	22.8	18.1
	0 N	21.5	9.3	11.4	24.2	21.1	13.1
		P(F)	LSD(Sidak)		P(F)	LSD(Sidak)	
Effects	Treatment	0.000	–		0.420	–	
	Year	0.000	–		0.000	–	
	Interaction	0.000	5.3		0.000	3.8	
N uptake [kg N ha^{-1}][a]	CONV	253.3	186.0	115.6	287.1	222.4	197.9
	MT	243.0	183.9	127.2	257.1	250.1	186.0
	COM1	42.7	40.6	46.7	246.9	220.0	140.6
	COM2	63.4	56.0	55.9	261.1	202.5	161.6
	0 N	178.0	57.5	81.8	253.5	177.2	113.9
		P(F)	LSD(Sidak)		P(F)	LSD(Sidak)	
Effects	Treatment	0.000	–		n.s.	–	
	Year	0.000	–		0.000	–	
	Interaction	0.000	53.3		0.011	56.1	

[a] Mean values for treatments and years were not reported as the interaction was significant.

Table 5

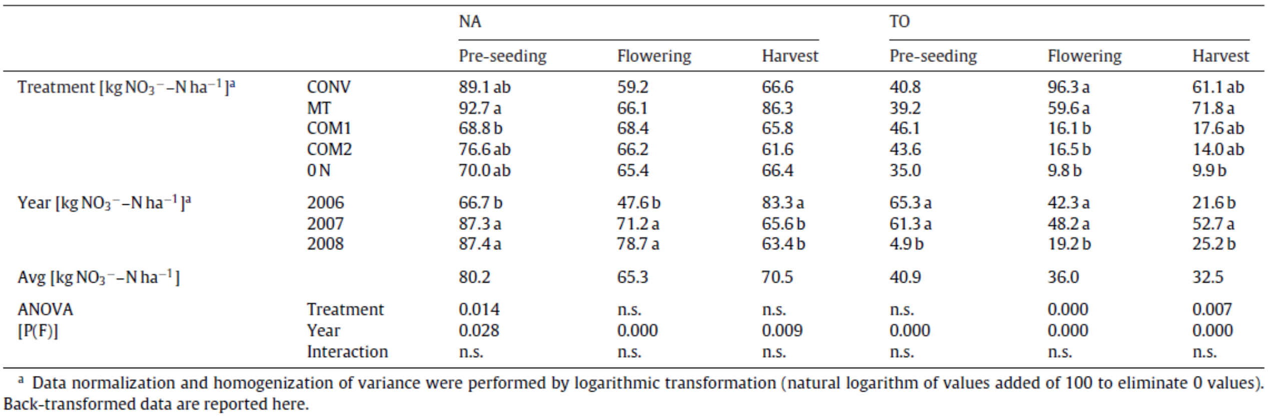
Total biomass and N uptake of the different treatments at NA and TO in 2009. The following were the studied treatments: moldboard plowing after urea fertilization (CONV), minimum tillage after urea fertilization (MT), compost supplied at two levels (COM1 and COM2) followed by moldboard plowing, and non-N-fertilized control plowed by moldboard (0 N).



	Total biomass		N uptake	
	NA (Mg d.m. ha^{-1})	TO (Mg d.m. ha^{-1})	NA (kg N ha^{-1})	TO (kg N ha^{-1})
CONV	8.3	24.0	49.5	217.3
MT	7.4	21.6	47.0	198.8
COM1	5.9	23.7	34.7	205.4
COM2	6.8	25.0	43.7	222.8
0 N	5.9	21.2	37.9	155.0
ANOVA, P(F)	n.s.	0.016	n.s.	0.016
LSD (Sidak)	–	3.7	–	59.9

Table 6

Soil nitrate-N content (SN) in the 0- to 60-cm layer in the different treatments at NA and TO during the three years of treatment application (2006 to 2008). The following were the studied treatments: moldboard plowing after urea fertilization (CONV), minimum tillage after urea fertilization (MT), compost supplied at two levels (COM1 and COM2) followed by moldboard plowing, and non-N-fertilized control plowed by moldboard (0 N).

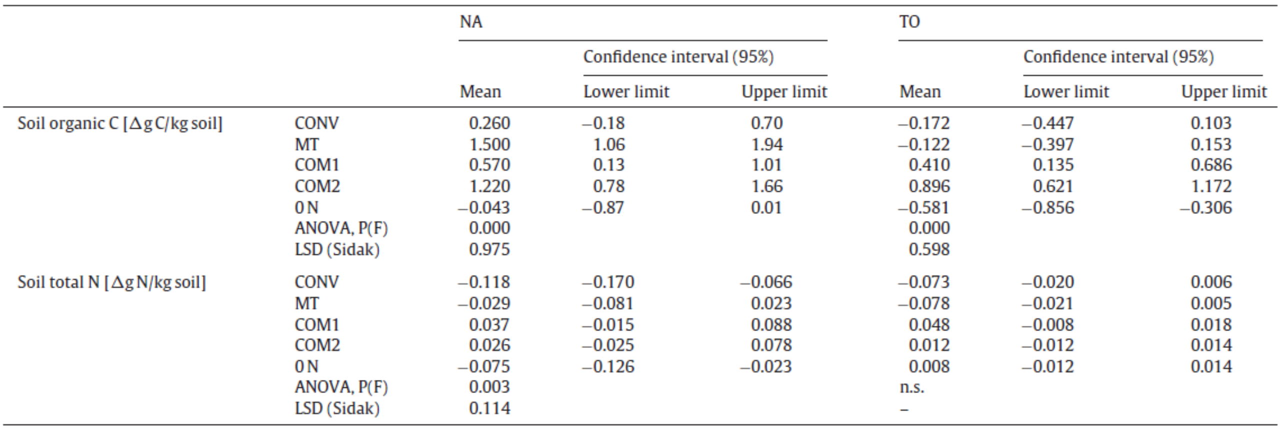


		NA			TO		
		Pre-seeding	Flowering	Harvest	Pre-seeding	Flowering	Harvest
Treatment [kg NO_3^-–N ha^{-1}][a]	CONV	89.1 ab	59.2	66.6	40.8	96.3 a	61.1 ab
	MT	92.7 a	66.1	86.3	39.2	59.6 a	71.8 a
	COM1	68.8 b	68.4	65.8	46.1	16.1 b	17.6 ab
	COM2	76.6 ab	66.2	61.6	43.6	16.5 b	14.0 ab
	0 N	70.0 ab	65.4	66.4	35.0	9.8 b	9.9 b
Year [kg NO_3^-–N ha^{-1}][a]	2006	66.7 b	47.6 b	83.3 a	65.3 a	42.3 a	21.6 b
	2007	87.3 a	71.2 a	65.6 b	61.3 a	48.2 a	52.7 a
	2008	87.4 a	78.7 a	63.4 b	4.9 b	19.2 b	25.2 b
Avg [kg NO_3^-–N ha^{-1}]		80.2	65.3	70.5	40.9	36.0	32.5
ANOVA	Treatment	0.014	n.s.	n.s.	n.s.	0.000	0.007
[P(F)]	Year	0.028	0.000	0.009	0.000	0.000	0.000
	Interaction	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

[a] Data normalization and homogenization of variance were performed by logarithmic transformation (natural logarithm of values added of 100 to eliminate 0 values). Back-transformed data are reported here.

Table 7

Soil organic C and total N concentration variations of the different treatments at NA and TO at the end of treatment application (harvest in 2008) relative to pre-treatment conditions (pre-fertilization in 2006). The following were the studied treatments: moldboard plowing after urea fertilization (CONV), minimum tillage after urea fertilization (MT), compost supplied at two levels (COM1 and COM2) followed by moldboard plowing, and non-N-fertilized control plowed by moldboard (0 N).



		NA			TO		
			Confidence interval (95%)			Confidence interval (95%)	
		Mean	Lower limit	Upper limit	Mean	Lower limit	Upper limit
Soil organic C [Δg C/kg soil]	CONV	0.260	−0.18	0.70	−0.172	−0.447	0.103
	MT	1.500	1.06	1.94	−0.122	−0.397	0.153
	COM1	0.570	0.13	1.01	0.410	0.135	0.686
	COM2	1.220	0.78	1.66	0.896	0.621	1.172
	0 N	−0.043	−0.87	0.01	−0.581	−0.856	−0.306
	ANOVA, P(F)	0.000			0.000		
	LSD (Sidak)	0.975			0.598		
Soil total N [Δg N/kg soil]	CONV	−0.118	−0.170	−0.066	−0.073	−0.020	0.006
	MT	−0.029	−0.081	0.023	−0.078	−0.021	0.005
	COM1	0.037	−0.015	0.088	0.048	−0.008	0.018
	COM2	0.026	−0.025	0.078	0.012	−0.012	0.014
	0 N	−0.075	−0.126	−0.023	0.008	−0.012	0.014
	ANOVA, P(F)	0.003			n.s.		
	LSD (Sidak)	0.114			–		