Impact of long-term compost amendments on soil fertility, soil organic matter fractions and nitrogen mineralization

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Abstract

Soil organic matter (SOM) is a major carbon (C) pool and can play a significant role in C mitigation measures. It is also a crucial factor for several soil physical properties and a major nutrient source for crops. To obtain an understanding of the changes that occur in the soil following long-term annual compost application, the Soil Service of Belgium started a long-term field trial in Boutersem, Belgium, in 1997. Here, 12 different treatments (fallow, unfertilized, mineral fertilized and nine compost treatments differing in intensity from 15 to 45 t ha^{-1} and in application frequency from annual to every 3 years) were implemented in four repetitions. All compost-amended treatments partially substituted the mineral nutrient requirements of the crop and had a positive influence on soil chemical and physical parameters. The continued application of compost also has important effects on the amount and distribution of SOM. To quantify this, soil samples from five treatments were divided into seven fractions differing in physical and biochemical protection levels of the associated SOM. Not only did the total amount of C in the amended soils increase significantly over the course of the experiment, it also increased specifically in the less-protected SOM fractions. These results were combined with a 217-day-long incubation experiment to investigate the influence of long-term compost fertilization, causing an altered SOM distribution, on soil respiration and nitrogen mineralization.

Keywords: compost, soil organic matter, nitrogen mineralization, soil organic carbon

INTRODUCTION

The use of compost in agriculture and horticulture could contribute significantly to the improvement of the chemical, physical and biological quality of the soil by maintaining and increasing the soil organic C (SOC) content (Barral et al., 2009; Nevens and Reheul, 2003). Moreover, agricultural soils are a major sink of CO_2 globally. The terrestrial SOC pool contains about 2.5 times more organic C than the vegetation and about twice as much C as is present in the atmosphere (Batjes, 1998). Over the last 150 years, cultivation and disturbance of agricultural soils have caused a net loss of between 40 and 90 Pg C globally (Lal and Bruce, 1999; Lal, 2004). These losses can be replenished by restoring degraded soils, converting marginal agricultural soils to restorative land use and adopting recommended management practices (Lal, 2004). Replenishing these C stocks has multiple benefits, for example, increasing soil water holding capacity and sequestering atmospheric CO_2. Considering agricultural land alone, approximately 5.5-6.0 Gt CO_2 eq could potentially be stored each year, which amounts to approximately one-sixth of global annual CO_2 emissions (Olivier et al., 2012; Smith et al., 2008).

There are still some questions on the long-term effects of the use of different types of compost, such as the vegetable, fruit and garden waste (VFG) compost produced in Belgium, on agricultural land, especially the effects on C sequestration, N mineralization and soil organic matter (SOM) fractions. The goal of this study was to analyse the long-term effects of repeated VFG compost applications in a typical arable crop rotation in Belgium, using a long-term field trial. The direct impact of VFG compost applications through its N fertilizing value on crop yields was measured for different application rates and frequencies. In addition, the long-term effect on SOC content, composition and dynamics was studied as well as the impact on the N-supplying capacity of the soil.

MATERIALS AND METHODS

In 1997, the Soil Service of Belgium set up a long-term field trial with VFG compost on a loamy soil in Boutersem, Belgium. The site has a maritime temperate climate, with a warm summer and significant precipitation in all seasons (no dry season). The average annual temperature and precipitation during the trial period were 11.0°C and 760 mm, respectively. The trial was set up as a randomized complete block design with 14 treatments. The site was divided into 48 plots, each measuring 10 by 10.5 m. Twelve treatments were laid out in four-block replicates, including an unfertilized control treatment, a control treatment with only mineral fertilization, three treatments with VFG compost amendments every 3 years (15, 30 and 45 t ha^{-1}), three with VFG compost amendments every 2 years (15, 30 and 45 t ha^{-1}), three with yearly applications of VFG compost (15, 30 and 45 t ha^{-1}) and an unfertilized fallow plot.

Since 1997, a crop rotation of sugar beet, winter wheat, potatoes and carrots has been applied. The VFG compost was applied before the growing season (in spring for the root crops and just before sowing for the winter cereals) (Tits et al., 2012).

The N content at the beginning of the growing season was used as input for the N-INDEX expert system (Geypens et al., 1994) to calculate the N fertilization needed for each treatment. The N fertilization of the different trial treatments was applied as follows: treatment 1 received no N fertilization; treatment 2 always received mineral N fertilization according to the N fertilization recommendation. Treatments 3 to 11 received no mineral N fertilization during the first trial years (1997-2002). However, starting from 2003, the expected amount of N released by the compost applied during the growing season was supplemented each year with mineral N fertilizer up to the recommended level. The average percentages of nutrients in VFG compost that would be available for the crops during the next growing season are estimated to be 10-20% for N, 50% for P, 80% for K and 20% for Mg (http://www.vlaco.be). And on average the compost contained 15% C.

In 2011, soil physical parameters were analysed in four of the treatments. Bulk density and macroporosity were measured on undisturbed Kopecky ring samples, three in each plot, taken at a depth of 15 cm. Infiltration capacity was measured using the double ring method, on three replicates within each plot. In 2008, earthworm numbers and mass were determined by pouring a mustard extract over 1 m^2 and afterwards digging the soil out to 20 cm to isolate the worms.

The compost used in this study was VFG compost, provided by the company EcoWerf. Prior to each compost application, a representative sample was taken and analysed. Each year, the composition of the composts applied approached the average composition of VFG compost (Vlaco, 2011), the heavy metals were far below the legal standards and the composts contained very low amounts of stones and impurities and no viable seeds.

In February 2012, five treatments were selected for a more in-depth study of the SOM fractions and mineralization. Samples were taken to a depth of 30 cm on each of the four plots of these treatments before compost application. For the incubation experiment and SOM fractionation, a more detailed sampling was conducted. The five treatments sampled for this experiment were the unfertilized control, the mineral-fertilized control, the application of VFG compost every 3 years at 45 t ha^{-1} and two yearly applications of VFG compost at rates of 15 and 45 t ha^{-1}. In each of four replicates of all treatments sampled, eight soil cores were taken 2 m apart, from 0-30 cm depth, and mixed to form a composite sample. The samples were dried at 45°C, crushed and sieved to <2 or <8 mm, depending on the subsequent fractionation scheme.

A fractionation scheme, based on that described by Six et al. (2002), was used on these samples. It distinguishes five SOM pools with varying degrees of physical and (bio)chemical protection as illustrated in Figure 1. Subsequently, 8-mm-sieved soil is passed over 250- and 53-µm sieves, yielding a macro-aggregate fraction (M) larger than 250 µm, a free micro-aggregate fraction (m) between 250 and 53 µm and a free silt and clay fraction (s+c) smaller than 53 µm. Afterwards, the M fraction is passed through the micro-aggregate isolator, a device that breaks the macro-aggregates using small glass beads. The occluded silt and clay fraction (s+c M) and occluded micro-aggregate fraction (mM) are washed through a 250 µm mesh by a constant water stream, the particulate organic matter (POM) (larger than 250 µm) fraction is left on top. The mM and s+c M fractions are subsequently separated by a 53 µm sieve. The procedure is described in detail by Six et al. (2002). All samples were analysed for C and N content with an elemental analyser (Flash 2000, Thermo Scientific, Massachusetts, USA) coupled with a mass spectrometer (Isoprime GV Instruments, Manchester, UK).

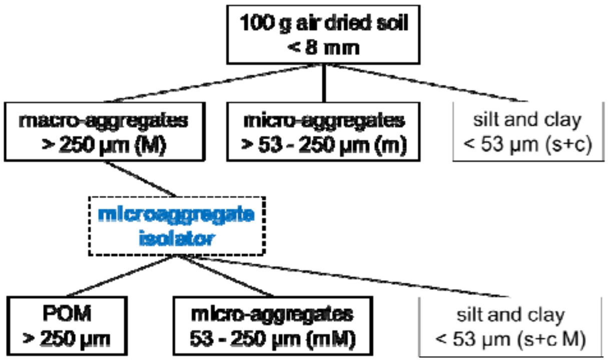

Figure 1. Fractionation scheme based on that of Six et al. (2002) dividing the SOM in an unprotected particulate organic matter fraction (POM), two physically protected fractions (m and mM) and two physically and (bio)chemically protected fractions (s+c and s+c M).

The incubation experiment was set up for 217 d at 60% water-filled pore space (WFPS) and 25°C. Nitrogen mineralization was measured on day 0, 154 and 217 in separate jars with 50 g dried and 2-mm-sieved soil at 60% WFPS and 25°C. Mineral N (ammonium and nitrate) was measured with a continuous flow analyser (SA-40, Skalar Analytical B.V., Breda, Netherlands).

The statistical packages R 3.0.1 (R Core Team, 2013) and JMP Pro 11.0.0 (SAS Institute Inc., Cary, NC, USA) were used for all data analysis. To determine significant effects and interactions, analysis of variance (ANOVA) was applied. Tukey's HSD test was used to test equality of treatment means. Means followed by the same letter do not significantly differ from each other with a certainty higher than 95%.

RESULTS AND DISCUSSION

Crop yield data has been collected for each plot in the experiment since 1997. Overall, none of the VFG treatments differed in yield significantly from the treatment fertilized with minerals. The unfertilized plots always gave the lowest yields, but the difference from the fertilized treatments varied from year to year and crop to crop. However, after 17 years, the difference seemed to become gradually larger as can be seen in Figure 2. In this figure, the relative yields of the treatments with VFG application are compared with the yield of the mineral-fertilized control during the whole period (mineral control = 100%). Starting from 2003, the N fertilization in all the treatments with VFG compost was supplemented with mineral fertilizer to the recommended amount calculated with the N-INDEX system. In previous years, these treatments only received VFG compost according to the trial setup, mostly resulting in a sub-optimal N fertilization for the crop. Figure 2 shows clearly that, since 2003, all the treatments with VFG compost showed yields equivalent or slightly higher than that of the mineral-fertilized control. This indicates that the VFG compost can replace a significant amount of the mineral fertilizers needed for optimal crop growth.

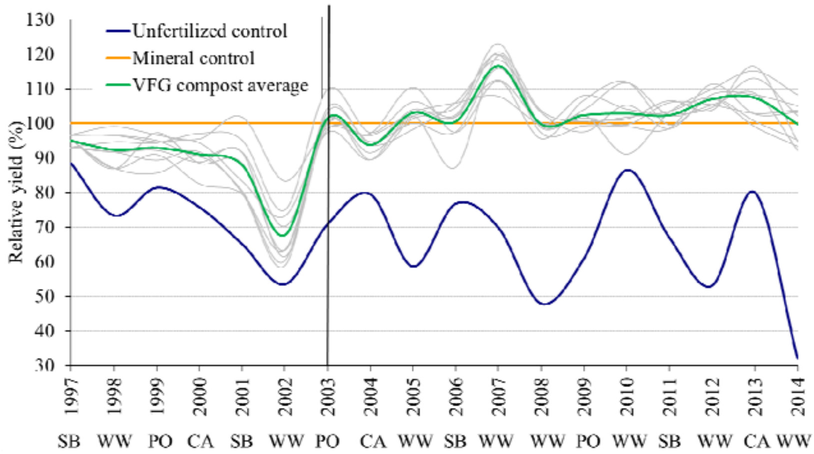

Figure 2. Yield (%) of unfertilized (blue) and VFG compost-amended (grey with mean in green) treatments relative to the mineral control treatment from 1997 until 2014 of the VFG compost experiment in Boutersem, Belgium.

In Table 1, some physical and biological parameters are displayed for the mineral control and three VFG compost treatments. It is clear that the long-term compost addition has significantly decreased bulk density and increased macroporosity and infiltration capacity compared with the mineral-fertilized control. As earthworms are an important indicator of soil biological health, in 2008, the number and mass of earthworms in these five treatments was measured. No significant differences could be found, but a clear upward trend with increasing compost addition is visible in the data, for both the number of worms and the total worm mass.

Table 1. Soil physical (2011) and biological (2008) characteristics of four treatments of the VFG compost experiment in Boutersem, Belgium.

Treatment	Bulk density (g cm^{-3})	Macroporosity	Infiltration capacity (cm day^{-1})	Earthworms	
				Number m^{-2}	g m^{-2}
Mineral-fertilized control	1.46 ^{a}	6.24 ^{b}	661 ^{b}	90	40
45 t VFG ha^{-1}, three-yearly	1.42 ^{ab}	8.53 ^{a}		66	59
15 t VFG ha^{-1}, yearly	1.39 ^{b}	10.02 ^{a}	1134 ^{ab}	115	77
45 t VFG ha^{-1}, yearly	1.38 ^{b}	8.72 ^{a}	1173 ^{a}	159	84
p-value	0.0015	<0.0001	0.0446	ns	ns

During the experiment, an increase in mineral N residue at the end of the growing season was found in the treatments with the highest yearly VFG compost additions (Tits et al., 2012). It was hypothesized that the N mineralization rate and/or the capacity of these treatments was no longer correctly predicted by the N-INDEX model due to changes in the SOM properties. Five treatments were selected for a detailed study of the SOM content and dynamics. In Figure 3, the C content of five SOM fractions, isolated with the procedure displayed in Figure 1, are indicated. For all fractions measured, the C concentration was significantly higher for the treatment with the largest addition of VFG compost. Between the unfertilized treatment (G1) and the mineral control (G2), no differences were observed. Also, the treatments with 45 t compost ha^{-1} added every 3 years (G5) and 15 t ha^{-1} compost added yearly (G9) did not present a significantly different C content. Since 1997 (initial C content 0.9%), the C content almost doubled in the treatment with 45 t compost ha^{-1} year^{-1} (G11), increased by 30% in both other compost treatments and decreased slightly in both treatments without organic fertilization.

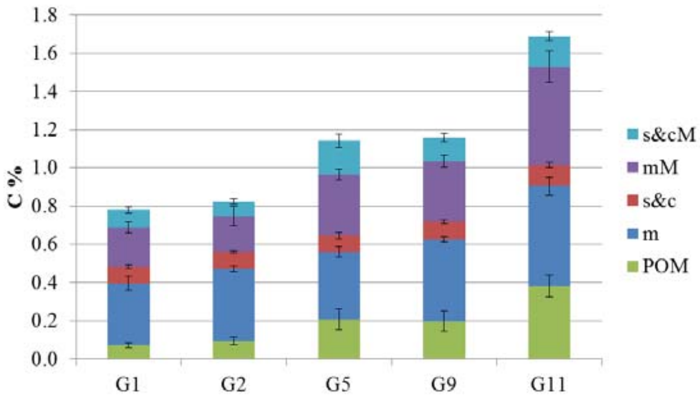

Figure 3. Carbon concentrations (%) of five major SOM fractions derived from five treatments from the experimental site in Boutersem, Belgium. Samples were taken in February 2012.

As shown in Figure 3, the extra C found in the treatment with an annual amendment of 45 t compost ha^{-1} since 1997 was concentrated in three fractions. One third could be found in the POM fraction, one third in the intra-macro micro-aggregate fraction (mM) and about 20% in the free micro-aggregate fraction (m). The higher the compost dose, the larger the contribution of the free micro-aggregates to the total C increase.

This sequence is in agreement with the aggregate formation theory described by Six et al. (2004) and Segoli et al. (2013) were the fresh residue is converted to POM and serves as the core of newly formed macro-aggregates. Inside these macro-aggregates the POM is further degraded and occluded micro-aggregates are formed. Part of the organic matter is bound to the mineral soil particles (silt and clay fraction) and part is incorporated in the newly formed micro-aggregates. After a while, the macro-aggregates disintegrate and the micro-aggregates and silt and clay particles are freed.

In Figure 4, the net N mineralization of the selected treatments is displayed for a 217 d period. Significant differences in mineralization were found between the treatments with and without VFG compost application and between the treatment with 45 t VFG ha^{-1} added yearly and the other treatments. Adding 45 t ha^{-1} VFG compost once every 3 years or spread out evenly over the years yielded the same mineralization rate. Both treatments without VFG compost addition also yielded the same N mineralization curve, notwithstanding the higher input of crop residues due to significantly higher yields in the mineral-fertilized treatment compared with the unfertilized control.

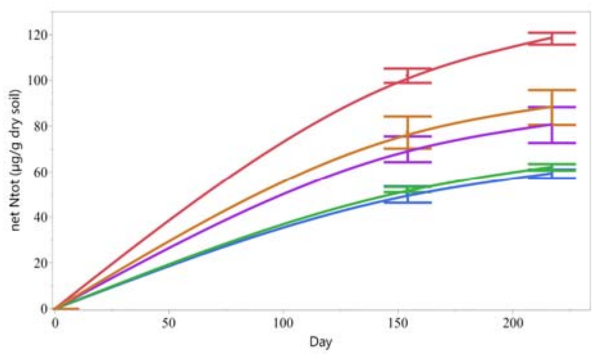

Figure 4. Net nitrogen mineralization over a 217 d period of five treatments from the VFG compost experiment in Boutersem: unfertilized control (blue), mineral-fertilized control (green), 45 t VFG ha^{-1} added three-yearly (purple), 15 t VFG ha^{-1} added yearly (yellow) and 45 t VFG ha^{-1} added yearly (red). Whiskers display standard error.

In Figure 5, the specific N mineralization, mineral N production per unit of C in the soil, is plotted for each of the five treatments studied. No significant differences could be found between the treatments. In this lab incubation experiment, the mineral N production capacity was equal in all treatments.

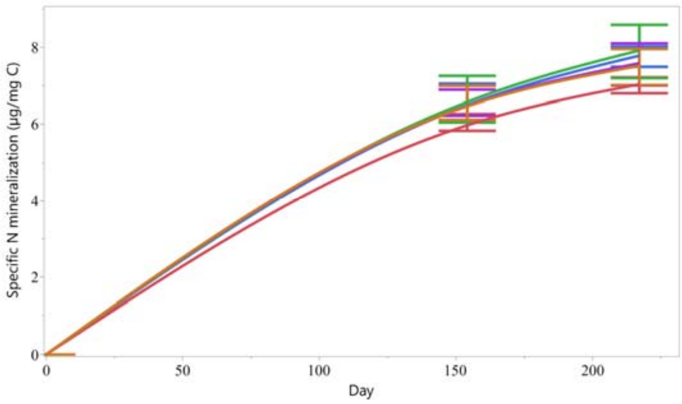

Figure 5. Specific nitrogen mineralization (µg N mg^{-1} C in the soil) over a 217 d period of five treatments from the VFG compost experiment in Boutersem: unfertilized control (blue), mineral-fertilized control (green), 45 t VFG ha^{-1} added three-yearly (purple), 15 t VFG ha^{-1} added yearly (yellow) and 45 t VFG ha^{-1} added yearly (red). Whiskers display standard error.

CONCLUSIONS

The continued application of VFG compost has important effects on the physical and biological parameters of soil. After 17 years, the treatments which received intense compost fertilization showed a significantly lower bulk density, increased macroporosity and infiltration capacity and an upward trend in number and weight of earthworms. Besides, it was found that the VFG compost could replace mineral fertilizers partly (and for the highest dose completely) for 17 consecutive years without any significant yield loss.

Also, the amount and fraction distribution of SOM in the soil were significantly affected by the continuous VFG compost application. Since 1997 (initial C content 0.9%), the C content almost doubled in the treatment with 45 t compost ha^{-1} $year^{-1}$ and decreased slightly in both treatments without organic fertilization. The extra C found in the treatment with an annual amendment of 45 t compost ha^{-1} was concentrated in three youngest fractions as suggested by the aggregate formation theory (the POM fraction, intra-macro micro-aggregate fraction and the free micro-aggregate fraction). The higher the compost dose, the larger the contribution of the free micro-aggregates to the total C increase.

The 217-day-long incubation showed a significant increase in the N mineralization potential of the compost-amended soils, but no increase in the N mineralization per unit of soil C. This could not explain the deviations observed in the field by Tits et al. (2012), where the N-INDEX model underestimated the N mineralization (based on the SOM content) in the treatments with continuous high compost fertilization. Possibly, this effect can be attributed to the fact that the incubation experiment, set up with sieved soil and under optimal temperature and moisture conditions, was not able to encompass the increased soil physical and biological properties of the compost-amended soil. Further research will be needed to explain the underestimation of N mineralization in soil amended with high loads of compost.

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