Soil physical properties of a Luvisol developed on loess after 15 years of amendment with compost

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Abstract

Recycling composted organic residues in agriculture can reduce the need for mineral fertilizers and improve the physicochemical and biological properties of cultivated soils. However, more studies dealing with soil physical properties after compost amendment are still needed. The objective of this study was to investigate the impact of long-term compost amendment on soil physical properties in a silt loam Luvisol under a maize-wheat rotation in the Paris Basin. Since 1998, three composts and one manure were applied every second year after wheat harvest, at a rate of ca. 4 Mg C ha^{-1}. Bulk density, organic carbon concentration on a mass basis, water holding capacity, gas transport properties and Atterberg limits were measured on topsoil samples taken 15 years after the beginning of the experiment. Soil moisture was monitored in the field down to a depth of 160 cm during two years with different climatic conditions: a year with a dry summer (2010) and a year with a wet summer (2012). Compost and manure amendments reduced bulk density and increased organic carbon concentrations, which improved apparent air permeability and gas diffusivity, but only one of the amendments (a green waste-sewage sludge compost) increased water-holding capacity. The amendments also increased the water contents at the Atterberg limits and overall produced better soil conditions for tillage and other agricultural operations, in particular in wet years. However, field moisture measurements showed that in general, soil water contents were not higher in the amended soils than in the control at any of the periods considered.

Keywords: Organic waste; organic amendment; soil water; manure; water retention; gas diffusion.

1. Introduction

Recycling of the organic matter contained in urban wastes as soil amendments after composting is nowadays a common practice worldwide. It allows to counteract the decline in soil organic matter (SOM) that is widely recognized as a global problem of agricultural soils (Lal, 2007), as well as to improve waste management strategies (Hargreaves et al., 2008; Farrell and Jones, 2009). As a result, composts from a variety of origins are being produced and used as amendments in agriculture. The relative novelty of using these products, in addition to the diversity in their composition and properties makes a careful examination of their effects on the soil-plant system necessary. An increasing number of field experiments under different agricultural systems have been established in the last twenty years, in order to test the effects of compost produced from urban wastes in soil and agricultural systems, mostly on cereal crops, in China (Xin et al., 2016), Canada (Miller et al., 2015), Belgium (Arthur et al., 2011; Vanden Nest et al., 2014), France (Houot et al., 2009), or Denmark (Magid et al., 2006). Several advantages of compost use have been found in those experiments, including increases of SOM and nutrient availability to plants, reductions of bulk density and increases in aggregate stability. Negative effects of compost use have also been reported, in particular related to potential toxicity issues due to the presence of high concentrations of potentially toxic trace elements in some urban waste composts (Smith 2009; Lopes et al. 2011; Paradelo et al. 2011). In what concerns crop production, positive effects on yield may not be observed in the short-term or at low compost loads; however, increases are obtained in the long-term, once soil properties such as structure ameliorate and organic N from compost becomes available to plants (Diacono and Montemurro 2010).

Regarding the studies dealing with compost effects on agricultural soil, physical properties are overall less well understood and studied than other properties. This could

69 be explained by the fact that the modification and evolution of soil physical properties in
70 response to amendments and fertilizers are in general slower than properties such as
71 nutrient concentrations or pH. Notwithstanding, the study of physical properties such as
72 water holding capacity, porosity or compactability is important for agriculture: they have
73 significant impacts on agricultural operations such as tillage or seeding, as well as on
74 productivity through water supply to crops (Carter, 2007; Leroy et al., 2007; Arthur et al.,
75 2011). In this paper, we report physical properties of compost-amended soils from the
76 long-term field experiment QualiAgro, in Northern France. The experiment was
77 established in 1998 in order to study the impacts of the reutilization of organic wastes in
78 agriculture and it has produced data on different aspects of compost use that have been
79 published in a series of recent papers (Annabi et al., 2011; Cambier et al., 2014; Filipović
80 et al., 2014; Noirot-Cosson et al., 2016; Paetsch et al., 2016; Obriot et al., 2016; Sadet-
81 Bourgeteau et al., 2018; Cambier et al., 2019).
82 Our objective was to investigate how organic amendments affect physical properties,
83 with special focus on soil structure, water holding capacity and porosity, and soil water
84 content during summer. All these are important properties for the functioning of
85 agricultural soils: porosity, water-holding capacity and gas transport are essential for
86 water supply to crops and soil aeration (Marshall et al., 1996). Soil water content in
87 summer is critical for maize production, because this crop is rainfed in Northern France,
88 so it depends entirely on water supply from the soil during dry periods.
89
90 **2. Material and Methods**
91
92 2.1. Study site
93 The field experiment was set up in Feucherolles (Yvelines, France), in the western part

of the Paris Basin, as part of the QualiAgro long-term study (Houot et al., 2009). Site annual average precipitation and temperature are 583 mm and 11°C, respectively (data recorded at on-site weather station). The soil is a Haplic Luvisol (IUSS Working Group WRB, 2014) developed on quaternary loess decarbonated through more than 1 m, typical for arable soils of the Paris Basin. The soil profile presents the following sequence of horizons:

- Ap1, 0–28 cm, a silty horizon ploughed every year (787 g kg^{-1} silt, 152 g kg^{-1} clay)
- Ap2, 28–35 cm: plough pan or former bottom of a deeper plough horizon
- E, 35–50 cm: eluviated horizon, clayey silt
- Btg, 50–90 cm: argic horizon, clay, showing redoximorphic features
- Btg/C, 90–140 cm: argic horizon mixed with decarbonated loess, silty clay.

The experiment is composed of 40 plots of 450 m^2, separated by buffer strips (Figure 1). It is a randomized 4-block experiment, split in two half-parts corresponding to two levels of mineral N fertilisation (Houot et al., 2009). The present study focuses on the 20 plots that receive an optimum level of N fertilization: 140 kg N ha^{-1} for wheat and 82 kg N ha^{-1} for maize. Four different organic amendments have been applied: a municipal solid waste compost (MSW) obtained from aerobic composting of mechanically-separated organic fractions from residual waste after selective collection of dry and clean packaging; a biowaste compost (BIO) obtained from co-composting of green wastes and source-separated organic fractions of municipal solid wastes; a compost (GWS) resulting from the co-composting of green waste collected from private and public gardens (70%) and sewage sludge (30%); and a dairy farmyard manure (FYM) obtained from a nearby farm. These four organic treatments were compared to a control treatment that did not receive any organic amendment (CTR). The composts and manure have been applied

every second year starting 1998 in an amount of 4 Mg of organic carbon per ha, i.e., 2 Mg OC ha^{-1} $year^{-1}$ on average, which is about 2-times the mass flux commonly applied by farmers in similar conditions. This high load of organic matter is essential in order to increase SOM stocks in the intensively cultivated soils of the Paris sedimentary basin, that are prone to erosion and sealing due to weak soil structure and loss of SOM after decades of continuous cropping. Further details about the characteristics of the organic amendments employed can be found in Paetsch et al. (2016) and Cambier et al. (2019).

The field has been cultivated since 1998 with a biannual succession of winter wheat (*Triticum spp*.) and maize (*Zea mays* L.), without intermediate crop for simplification. The soil is plowed once every year in October or November with a four-furrow mouldboard plow (plowing width 160 cm) to an approximate depth of 28 cm. In late April or early May, N fertilization is done and the seedbed for maize sowing is prepared using a tined cultivator. Maize harvest takes place in October. Wheat sowing takes place in November, with mineral N applied twice on February 15th and March 28th. Urban waste composts and manure are applied over wheat stubble every second year in early September and disking (depth 25 cm) is immediately carried out to incorporate composts and stubbles within the upper soil layer. A more detailed calendar of the agronomic practices can be found in Filipović et al. (2014), whereas yield values can be found in Noirot-Cosson et al. (2016).

2.2 Soil sampling and analysis

Soil sampling was carried out in spring 2013, when undisturbed and disturbed soil samples were collected in the 20 plots of the N optimum block. Soil organic carbon concentration, *OC*, and the plastic limits were measured in disturbed samples, whereas undisturbed samples were used for bulk density, ρ_b, water retention and gas transport

144 measurements. Soil organic carbon contents were determined by catalytic combustion
145 using a Carlo Erba Elemental Analyser NA 1500 Series 2 on air-dried 2 mm-sieved
146 homogenized samples made up from 10 to 15 individual samples taken from each plot.
147 Bulk density was determined on 470-cm^3 undisturbed soil cores sampled in three
148 replicates per plot.

149 The soil water-holding capacity was determined on 50-cm^3 undisturbed soil samples,
150 subsequently drying the samples to various matric potentials using a Richards pressure
151 plate apparatus, for the driest point at -15500 hPa disturbed soil was used. Field capacity
152 (FC) was defined here as the water content at a matric potential of -100 hPa, and the
153 wilting point (WP) as the water content at a matric potential of -15500 hPa. The difference
154 between the two values is the available water capacity (AWC).

155 The Atterberg limits (plastic and liquid limits) (Atterberg, 1911) were determined on
156 disturbed samples, with four replicates for each plot. The plastic limit was determined
157 according to the Casagrande test, i.e. as the gravimetric water content at which a rolled
158 thread of freshly moulded soil with a diameter of 3 mm just begins to crack (British
159 Standard 1377, 1975). The liquid limit was determined using the traditional Casagrande
160 liquid limit apparatus (British Standard 1377). The difference between the liquid and the
161 plastic limits, known as the plasticity index, is the range of moisture content over which
162 a soil shows plastic behaviour.

163 Gas transport properties were determined on larger cores (470 cm^3), which were
164 slowly saturated and then drained to three matric potentials: -30 hPa, -100 hPa and -300
165 hPa. Apparent air permeability, k_a, was determined using a steady-state method and a
166 pressure gradient of 2 hPa. In order to avoid air leaking between the soil and the core, the
167 soil was gently pressed at the edge. Gas diffusivity was then measured on the very same
168 cores in a one-chamber device tracing oxygen. Assuming steady state diffusion, the O_2

diffusion coefficient (D_P) was determined from the logarithm in O_2 concentration difference within the chamber and free air in relation to time. To infer dimensionless relative gas diffusivity, D_P/D_0, the measured D_P were temperature-corrected and then divided by the oxygen diffusion coefficient in free air, D_0 (D_0=0.205 cm^2s^{-1}). More details on gas diffusivity and apparent air permeability measurements can be found in Martínez et al. (2016). Air-filled porosity, ε_a, was derived from water content and total porosity, Φ, the latter is calculated from bulk (ρ_b) and particle density. The tube equivalent pore diameter, d (µm), at a given water content can be approximated by d=3000/-h, where h is the matric potential (hPa) (e.g. Eden et al., 2017). The amount of (non-) complexed clay or OC was derived by determining n as the clay/OC ratio (Dexter et al., 2008). This ratio indicates the amounts of (non-) complexed clay (CC and NCC) and (non-) complexed OC (COC and NCOC), using $CC = (nOC)\ if\ (nOC < clay)\ else\ CC = clay$ and $NCC = (clay - CC)\ if\ (clay - CC) > 0\ \ else\ NCC = 0$ for clay (Dexter et el., 2008). The pore tortuosity-connectivity factor, X, was calculated by $X=log(D_P/D_0)/log(\varepsilon_a)$ (e.g. Currie, 1960; Currie, 1961). Pore organization, PO, as suggested by Groenevelt et al. (1984) and Blackwell et al. (1990) was derived by $PO=k_a/\varepsilon_a$. PO reflects the continuity or tortuosity of pores, particularly of macropores relevant for convective gas transport, where a larger continuity or smaller tortuosity is reflected by larger PO values and vice versa (Blackwell et al. 1990; Eden et al., 2011).

2.3 Field monitoring of soil water content

Soil water content was monitored every 10 to 14 days (growing season) in five of the plots (one of each treatment), which were equipped with time domain reflectometry probes at 20, 40, 60, 80, 100, 130, and 160 cm depth. A description of this equipment can be found in Cambier et al. (2014). In this work, we present moisture data from the

spring/summer period of 2010, which was a dry year (cumulated rainfall in the April-July period: 210 mm, total annual rainfall: 612 mm), and from 2012, which was a wet year (cumulated rainfall in April-July: 345 mm, total annual rainfall: 732 mm). Both 2012 and 2010 were years where maize was present in the field.

2.4 Statistics

In order to test the influence of the organic amendments on soil properties, treatment effects were analyzed by a model with organic amendment treatment as the main effect and field block as random effect. One-way ANOVA was performed followed by the Tukey *post-hoc* means comparison test to assess the significance of the differences between treatments. The variables were tested for normality using the Shapiro-Wilk test. All statistical tests were performed using the R statistical package for MacOSX (R Core Team, 2015).

3. Results and discussion

3.1 SOC, bulk density and porosity

Fifteen years of organic amendments addition increased soil OC contents with respect to the control soil (Table 1). GWS and BIO composts produced the highest increases in OC, what reflects differences in the composition and biodegradability of each compost: those materials with predominance of organic matter of low degradability will suffer lower OC loss by microbial mineralization and consequently, more OC will remain in the soil. This is the case for composts produced from green wastes (such as GWS and BIO composts), that are commonly rich in lignin and other compounds of low degradability. Clay and organic matter are main drivers of soil structural development, they therefore require special attention. Using the approach by Dexter et al. (2008) the clay/OC ratio was

219 determined. In the range of 8-11 *n* is at saturation, for this experiment all amended soils
220 lie within this range, whereas the control soil has *n*=14.5. In a long-term experiment on a
221 comparable silt-dominated loess soil *n* of unamended soils was also found to be higher
222 than that of manure-amended soils, moreover, they interpreted increasing *n* as an indicator
223 of increasingly degraded soil structure (Eden et al., 2012b). For the soils here this implies
224 a poorer soil structure especially for the control. The 1:10 line in Fig. 2 is based on the
225 threshold-value of n=10 provided by Dexter et al. (2008); when drawing a horizontal line
226 from any of the points to the Y-axis it indicates the amount of complexed clay (CC, above
227 the line) and non-complexed clay (NCC, below the line). For the control the lower arrow
228 in Figure 2 shows the amount of CC and NCC. While in BIO and GWS all clay is
229 complexed (compare upper arrow in Fig. 2), the amount of NCC increases in the order
230 FYM>MSW>control. De Jonge et al. (2009) reported poor tilth conditions for soils with
231 high *n*-values (e.g. above 11), due to the fact that NCC is more easily dispersed than CC
232 (Dexter et al., 2008). However, such observations were not made at Qualiagro.
233 The four organic amendments reduced soil bulk density and increased total porosity,
234 Φ, with respect to the control soil (Table 2), an effect that has been commonly observed
235 in compost-amended soils (Hargreaves et al., 2008; Diacono and Montemurro, 2010). At
236 -30 hPa the air-filled pore volume (made up of pores with an equivalent pore diameter, *d*,
237 ≥ 100 μm) of the amended plots was not significantly different from that in the control
238 plot, while the water-filled pore volume (≤ 100 μm) was significantly different for FYM
239 and BIO. At -100 hPa the air-filled pore volume (≥ 30 μm) did not differ for any treatment,
240 while the water-filled pore volume (≤ 30 μm) was significantly different for FYM. At -
241 300 hPa the air-filled pore volume (≥ 10 μm) was significantly larger for MSW and the
242 water-filled pore volume (≤ 10 μm) was significantly larger for FYM. This shows that in
243 comparison with the control, FYM has a larger volume of small pores (≤ 100, ≤ 30 and ≤

244 10 μm), even though the total volume is not significantly different. For BIO the difference
245 is significant in the smaller pore range (≤ 100 μm) and for MSW for larger pores (≥ 10
246 μm). For a Canadian sandy loam amended with compost, Carter et al. (2004) found an
247 increased macropore volume (*d*=50μm; -60 hPa) compared to the control under two of
248 three crops one year after compost application. In a silt loam the range of total porosities
249 revealed that compost addition gave rise to the largest pore volumes encountered
250 compared to two other treatments including a conventional one (Eden et al. 2012a).
251
252 3.2 Gas diffusivity and apparent air permeability
253 While no significant differences between treatments were revealed, a trend towards larger
254 relative gas diffusivities in amended soils, linked to the larger available pore volumes, is
255 visible (Fig. 3). Overall, the control and the BIO and FYM treatments appear to have
256 similarly functioning soil structures as revealed by diffusive gas transport, as their D_P/D_0
257 vs air-filled porosity curves are very similar, with the only difference being the amount
258 of available air-filled pore space at a given matric potential (Fig. 3a). GWS and MSW
259 have larger air-filled porosities but not higher relative diffusivities than the other
260 treatments, which indicates more tortuous pathways than in the other soils. This suggests
261 that GWS and MSW influenced soil structure and its functionality more pronounced than
262 BIO and FYM. This is also reflected in the pore tortuosity-connectivity factor, *X*, which
263 displays slightly higher averages for MSW and GWS than for the control, BIO and FYM
264 (Table 2). A negative relation between *X* and bulk density can be seen in the present study
265 and has also been observed in a study investigating gas diffusivity in a compost-amended
266 silt loam soil (Eden et al. 2012a). Overall, the pores in all treatments are well-connected,
267 as they are close to or even below the factor suggested by Buckingham (1904): $D_P/D_0=\varepsilon_a^2$,
268 where the exponent denotes X=2. Moreover, this simple model describes the measured

data rather well, especially MSW (Figure 3). Another simple model, $D_P/D_0=0.66\varepsilon_a$ (Penman 1940), which also provides an upper limit for diffusion measurements, overestimates the data for compost-amended soils, as also observed by Eden et al. (2012a).

The control soil displays the lowest overall apparent air permeability at -30 hPa, but at consecutively drier conditions this minor difference disappears (Table 2). In Figure 3 pore organization, *PO*, is shown along with apparent air permeability isolines as a function of air-filled porosity. Using *PO* air-filled porosity is contained in both axes (directly in the x-axis and indirectly in the y-axis) and thus has a large impact on the graph, which shows the treatments being slightly offset from one to the next in terms of increasing air-filled porosities in the order CNT<FYM<BIO<GWS<MSW. However, it appears that the overall shapes of the *PO* vs air-filled porosity curves have alike curvatures for all treatments. That means that the available pore space functions much the same for all treatments irrespective of the total amount of available air-filled pore space, the difference being the amount of gas conducted. The treatments seemingly did not induce big differences in terms of pore organization in this soil moisture range. With increasing air-filled porosity at the consecutive drainage levels (from -30 to -300 hPa) the continuity of pores increases as reflected by larger *PO* values, while tortuosity decreases.

Previous studies with compost-amended soils have shown different results. In a silt loam compost addition decreased relative diffusivity and bulk density and increased air-filled porosity (Eden et al. 2012a). This can be interpreted as an indicator of a pipe-like structure in more dense soils very effectively conducting gas, whereas less dense soils display a rather sponge-like structure. This observation is further confirmed by *X*, which was slightly lower for their control, indicating better-connected pores (Eden et al. 2012a). Overall, the diffusivities measured here at -100 hPa are lower, but so are the air-filled porosities (Fig. 3, Table 2); *X* is in a similar range in this study (Table 2), but no clear

differences between the control and the compost-amended soils can be discerned. The compost-amended soils of Eden et al. (2012a) had air permeabilities in the range between ~10-100 μm² and *PO*-values roughly between ~50-500 μm² at -100 hPa for individual samples, reaching higher values than its conventional counterparts. After 16 years of treatment that soil thus displayed a minor effect of compost addition on soil structure and functionality, whereas our French soil does not show a comparable influence after 15 years. However, the largest *PO*-values are found in the control, which is owed to the lower air-filled porosities, making pores in the control soil less tortuous. In turn the pores in amended treatments are more tortuous than the control, as indicated by lower *PO*-values (Fig. 3). Overall, all treatments (amended and control) have rather high POs, similar to Eden et al. (2012a), and hence are more pipe-like, however, with opposite impact of compost addition as compared to the aforementioned study. While Carter et al. (2004) reported an increased oxygen diffusion rate after compost addition, it had no impact on apparent air permeability, which was found to be consistently high with values >100 μm² at -60 hPa. This is to some extent unexpected, as the macropore volume was larger than in the control under two of their crops (Carter et al., 2004).

The lack of impact of the organic amendment additions on gas transport properties could reflect the fact that the organic amendments used here are not contributing to the formation of new aggregates and new porosity, moreover, this could also be related to particularities of the parent material, loess. The aforementioned comparable loess soil (Eden et al., 2012b) displayed considerably lower diffusivities and air permeabilities in the respective range of water contents (up to -300 hPa) after 106 years of treatment. This indicates a better soil structure in the soil studied here, which is capable of conducting more gas by diffusion at a given water content. This is further confirmed by the critical range of relative diffusivity (0.005 to 0.02) for adequate aeration for root growth as

provided by Stepniewski (1980; 1981). All soils are above the lower limit at -30 hPa and at or above the upper limit at -100 hPa, FYM already reaches the upper limit at -30 hPa. Eden et al. (2012b) suggested that the high silt content hampered soil structural development. Accordingly, large differences in the present study might not be expected for gas transport and soil structural parameters.

3.3 Water holding capacity, plasticity indexes and field water content

The effect of the organic amendments on water-holding capacity is shown in Table 1 and Figure 4. Only the addition of GWS increased significantly water content at field capacity with respect to the control, whereas the other amendments produced increases that were not significant at $p<0.05$. None of the amendments increased the wilting point with respect to the control soil. Available water capacity also increased in the soils amended with GWS, while it remained unchanged in the others. According to the literature, increments in available water-holding capacity following organic amendments would be expected (Hargreaves et al., 2008; Diacono and Montemurro, 2010; Eden et al., 2017), as a consequence of the general increase in porosity (relevant for field capacity) and surface area (relevant for the wilting point) induced by organic matter (Khaleel et al., 1981). But here, the modifications in SOM contents and/or quality were not large enough to produce a significant effect on water holding capacity, with the exception of the GWS treatment, that also presented the lowest bulk density and highest total porosity values (Table 2). Given that the amounts applied of all the amendments are similar on an OC basis (4 Mg OC ha^{-1}), this result strongly suggests that differences are due to the nature or quality of the organic matter added, likely through an indirect effect related to the improvement of soil structure. In this sense, Annabi et al. (2011) observed that, until 2007, aggregate stability increased in all amended soils with respect to the control, but differences among

composts were not observed at that moment. However, aggregate stability was not studied in the years 2010 and 2012, and differences that did not happen in the short term might be evidenced later: there is abundant evidence in the literature proving that, in the long term, amelioration of aggregate stability is responsible for increases in porosity and water holding capacity (Diacono and Montemurro, 2010) and that this effect depends not only on the amount added, but also on the nature of the organic amendment (Abiven et al., 2009).

Comparison of the absolute values of field capacity and the Atterberg's limits is relevant for agricultural operations. The four amendments increased the water contents at the plastic and liquid limits with respect to the control, although the plasticity index did not increase significantly (Table 1). This fact is directly related to the increase of SOC contents in the amended soils, as positive correlations between SOC and the Atterberg limits have been reported in several laboratory and field studies (Paradelo et al., 2007, 2009; Hemmat et al., 2010; Keller and Dexter, 2012; Stanchi et al., 2015). From a practical point of view, the increment of Atterberg limits will reduce the risk of deterioration of soil structure during agricultural operations, which could happen if the soils were tilled or trafficked at moisture contents higher than the plastic limit (Dexter and Bird, 2001). In all the treatments, field capacity was lower than the plastic limit, which is a desirable condition from the point of view of workability (Keller and Dexter, 2012). Given that the optimum water content for tillage is slightly lower than the plastic limit (about 0.7-0.9 times the plastic limit according to Dexter and Bird, 2001), a soil with field capacity lower than its plastic limit will dry and reach a suitable moisture content faster than a soil with a plastic limit lower than field capacity. This is relevant for agricultural operations in early spring, when soils are moist after the winter rains and need to dry before preparation for summer crops. In that case, a soil that reached fast the

369 optimum conditions for tillage would give the farmer the possibility to enter the field
370 earlier.

371 Figures 5 and 6 show water contents in the top 20 cm during the spring and summer
372 of both years and profiles of soil water contents at three moments in 2010 and 2012,
373 respectively. As expected, the soils were drier at the upper parts of the profile (first 40
374 cm) than in deep horizons, in particular in summer, and temporal variations were larger
375 at the upper 40 cm. Water contents were almost constant throughout the soil profile in
376 winter, but as spring and summer advanced and the upper horizons became progressively
377 drier, deep soil horizons were not affected due to the high clay content of the Bt horizon
378 (50-90 cm). The evolution of surface soil water content was different through each of the
379 two years, as a consequence of the different climatic conditions, with more rainfall in the
380 summer of 2012 than in the same period of 2010. In 2010, after maize planting in late
381 April, field water contents decreased progressively until the rains of mid-June and then
382 dropped sharply, likely due to crop consumption, reaching minimum values by the middle
383 of September. In 2012, soil water contents remained in higher values than in 2010 until
384 late July, due to the higher amount of rainfall during the period (over average rainfall
385 from April to July). For the period of our interest (March to October), soil water contents
386 were always below field capacity in 2010, whereas in 2012 they were close to the field
387 capacity until the beginning of July, and lower from then on.

388 Regarding the effect of the organic amendments, they did not increase soil water
389 contents with respect to the control (Figure 6), except for the higher moisture values of
390 the GWS-amended soil during a short period in the summer of 2012 (measures of June
391 20th and July 2nd). In the dry summer year, soils amended with FYM and GWS were drier
392 than the control soil. In the wet year, the situation was different: the soils amended with
393 MSW and BIO composts were drier than the control, and no differences were observed

for the other treatments. In any case, these observations must be taken with caution because the measurements have only been made in one plot per treatment (Figure 1). From the point of view of workability, water contents were much lower than the plastic limit for all soils during the cultivation period in the dry year (2010, Figure 6), in particular in late April were soil preparation and maize sowing was done, so in that case there would be no problems for agricultural operations. In the wet year, when soil water contents were higher in general and even above the plastic limit at some moments, the addition of organic amendments improved workability, due to the combination of lower moisture and higher plastic limit of the amended soils.

4. Conclusions

The effect of repeated applications of four organic amendments (farmyard manure and three composts) on the physical properties of a silty loam Luvisol, under a wheat-maize succession, during 15 years, was evaluated. All the amendments increased soil organic carbon concentrations and porosity and reduced bulk density, improving apparent air permeability and gas diffusivity. The functionality of the pore space, as assessed by measurements of diffusive and convective gas transport revealed that the amended soils are better aerated due to differences in available air-filled pore space. The amendments also increased the water contents at the Atterberg limits, what overall produced better soil conditions for tillage and other agricultural operations, in particular in wet years. Despite these modifications of porosity, only one of the amendments (a green waste-sewage sludge compost) increased soil water-holding capacity, while monitoring of soil water contents in the field during two years with different amounts of rainfall showed that, in general, soil water contents were not higher in the amended soils than in the control at any of the periods considered. Overall, higher loads of organic amendments can be

419 recommended in order to improve even more physical properties in these agricultural
420 soils, that have been depleted of organic matter after a long history of intensive cropping.
421
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584 Table 1. Soil organic carbon (SOC) and physical properties of the soils for selected treatments. Mean ± standard deviation (n=4). Different letters
585 indicate statistically significant differences at a *P*-value of 0.05 (Tukey test). FYM: farmyard manure treatment; MSW: municipal solid waste
586 compost treatment; GWS: green waste and sewage sludge compost treatment; BIO: biowaste compost treatment.

	SOC g kg^{-1}	Plastic limit g g^{-1}	Liquid limit g g^{-1}	Plasticity index g g^{-1}	Field capacity cm^3 cm^{-3}	Wilting point cm^3 cm^{-3}	Available water capacity cm^3 cm^{-3}
Control soil	10.5 ± 0.2a	0.25 ± 0.006a	0.32 ± 0.004a	0.07 ± 0.01a	0.37 ± 0.01a	0.07 ± 0.01a	0.29 ± 0.01a
Amended soils							
FYM	14.9 ± 0.4c	0.28 ± 0.01b	0.35 ± 0.002b	0.07 ± 0.01a	0.36 ± 0.02a	0.08 ± 0.004b	0.28 ± 0.01a
MSW	13.2 ± 0.4b	0.27 ± 0.007ab	0.36 ± 0.01b	0.09 ± 0.02a	0.35 ± 0.01a	0.07 ± 0.01a	0.28 ± 0.02a
GWS	15.7 ± 0.2d	0.28 ± 0.01b	0.35 ± 0.01b	0.07 ± 0.01a	0.39 ± 0.01b	0.08 ± 0.004ab	0.31 ± 0.01b
BIO	16.1 ± 0.4d	0.27 ± 0.008ab	0.35 ± 0.007b	0.08 ± 0.01a	0.37 ± 0.02a	0.08 ± 0.007b	0.30 ± 0.01b

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589 Table 2. Soil physical properties of the large soil cores subjected to gas transport measurements. Mean ± standard deviation (n=4). Different letters
590 indicate statistically significant differences at a *P*-value of 0.05 (Tukey test). FYM: farmyard manure treatment; MSW: municipal solid waste
591 compost treatment; GWS: green waste and sewage sludge compost treatment; BIO: biowaste compost treatment.

	Total porosity	Bulk density	Air-filled porosity, ε_a ($cm^3\ cm^{-3}$)			Pore tortuosity, connectivity, X			Air permeability, ka (μm^2)			Volumetric water content, θ ($cm^3\ cm^{-3}$)		
	$cm^3\ cm^{-3}$	$Mg\ m^{-3}$	-30 hPa	-100 hPa	-300 hPa	-30 hPa	-100 hPa	-300 hPa	-30 hPa	-100 hPa	-300 hPa	-30 hPa	-100 hPa	-300 hPa
Control soil	0.459 ± 0.011a	1.43 ± 0.02b	0.09 ± 0.01a	0.11 ± 0.01a	0.12 ± 0.01a	1.9 ± 0.2	1.8 ± 0.1	1.7 ± 0.1	34 ± 24	80 ± 28	99 ± 23	0.37 ±0.01a	0.35 ± 0.00a	0.34 ± 0.00a
Amended soils														
FYM	0.488 ± 0.005ab	1.35 ± 0.01a	0.10 ± 0.01a	0.12 ± 0.01a	0.14 ± 0.01ab	1.8 ± 0.3	1.8 ± 0.2	1.7 ± 0.2	48 ± 20	78 ± 14	98 ± 12	0.39 ± 0.01b	0.37 ± 0.01b	0.35 ± 0.01b
MSW	0.504 ± 0.015b	1.31 ± 0.04a	0.13 ± 0.01a	0.15 ± 0.02a	0.17 ± 0.02b	2.1 ± 0.3	2.0 ± 0.2	2.0 ± 0.2	51 ± 17	77 ± 13	92 ± 14	0.38 ± 0.00ab	0.36 ± 0.00ab	0.33 ± 0.00a
GWS	0.507 ± 0.016b	1.29 ± 0.04a	0.12 ± 0.02a	0.14 ± 0.02a	0.16 ± 0.02ab	1.9 ± 0.1	1.9 ± 0.1	1.9 ± 0.1	53 ± 22	75 ± 21	95 ± 21	0.38 ± 0.01ab	0.36 ± 0.01ab	0.34 ± 0.01ab
BIO	0.491 ± 0.019b	1.35 ± 0.05a	0.10 ± 0.03a	0.12 ± 0.03a	0.15 ± 0.03ab	1.8 ± 0.1	1.7 ± 0.1	1.8 ± 0.2	61 ± 18	84 ± 12	102 ± 10	0.39 ± 0.01b	0.37 ± 0.01ab	0.34 ± 0.01ab

592

FIGURE CAPTIONS

Figure 1. Long-term experimental field QUALIAGRO (in grey: plots equipped for moisture monitoring). CTR: control treatment; FYM: farmyard manure treatment; MSW: municipal solid waste compost treatment; GWS: green waste and sewage sludge compost treatment; BIO: biowaste compost treatment.

Figure 2. Organic carbon versus clay in relation to the Dexter saturation line. The arrows exemplary indicate the amount of complexed (CC) and non-complexed clay (NCC) in two treatments. CNT: control treatment; FYM: farmyard manure treatment; MSW: municipal solid waste compost treatment; GWS: green waste and sewage sludge compost treatment; BIO: biowaste compost treatment.

Figure 3. Left: Relative diffusivity as a function of air-filled porosity at varying water contents (-30, -100 and -300 hPa). The lines indicate the models suggested by Buckingham (1904) and Penman (1940). Right: Pore organization, PO, as a function of air-filled porosity at -30, -100 and -300 hPa. Isolines of air permeability (k_a) indicate the measured range. CNT: control treatment; FYM: farmyard manure treatment; MSW: municipal solid waste compost treatment; GWS: green waste and sewage sludge compost treatment; BIO: biowaste compost treatment.

618 Figure 4. Soil water retention curves. Bars represent twice the standard deviation of the
619 mean. FYM: farmyard manure treatment; MSW: municipal solid waste compost
620 treatment; GWS: green waste and sewage sludge compost treatment; BIO: biowaste
621 compost treatment.
622
623
624 Figure 5. Evolution of soil water content at 20 cm during the spring and summer of 2010
625 (a) and 2012 (b). The striped area represents the range between the maximum and
626 minimum plastic limits of the soils (cf. Table 1). FYM: farmyard manure treatment;
627 MSW: municipal solid waste compost treatment; GWS: green waste and sewage sludge
628 compost treatment; BIO: biowaste compost treatment.
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630
631 Figure 6. Representative moisture profiles at different moments of the years 2010 (dry
632 year) and 2012 (wet year). Moisture profiles are representative of the measures taken in
633 the period indicated in the Figure. Exact dates for each profile are the following:
634 29/02/2010, 04/06/2010, 24/08/2010, 02/03/2012, 08/06/2012, 27/08/2012. FYM:
635 farmyard manure treatment; MSW: municipal solid waste compost treatment; GWS:
636 green waste and sewage sludge compost treatment; BIO: biowaste compost treatment.
637