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Phosphorus fertiliser form determined the allocation of root-derived organic carbon to soil organic matter fractions

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Abstract

The efficiency of soil organic carbon (SOC) sequestration as a suitable negative emission technology depends mainly on plant-derived organic carbon input and its allocation to stabilised SOC pools. These processes may be affected by fertiliser use and soil type. The purpose of this study was to investigate the effect of the organic fertiliser poultry manure compost, the mineral fertiliser rock phosphate and their mixture on organic carbon (OC) transfer from plant to soil. We studied also its allocation to protected SOC pools of a Luvisol and a Neoluvisol. We carried out a growth chamber experiment with ^{13}C-enriched atmosphere, where ryegrass plants were grown for 7 weeks on the two different soil types in the presence of the three different fertilisers. We quantified root-derived OC input in three SOC density fractions and soil microbial biomass at the end of the experiment. Our results indicated that addition of poultry manure compost and its mixture with rock phosphate led to more root biomass and more root-derived OC transfer to active pools compared to rock phosphate alone. The amendments with poultry manure compost also led to higher microbial biomass contents compared to mineral fertilisation due to higher available organic phosphorus. We also noticed variations in the dynamics of the stabilised OC pools amongst soils, which could be attributed to the different impacts of phosphorus fertiliser types on SOC stabilisation processes. We concluded that organic and mineral phosphorus fertilisers may have a contrasting impact on OC flow from plant to soil and in particular on the allocation of root-derived OC to labile or stable SOC fractions. The magnitude of these effects was more influenced by soil type than their pattern, which was similar for the two soil types.

Keywords: Poultry manure; Rock phosphate; C isotopes; SOM density fractionation

1. Introduction

To enhance soil organic carbon (SOC) sequestration in agricultural soils it is necessary to increase plant-derived organic carbon inputs (Chenu et al., 2019), requiring nitrogen (N) and phosphorus (P) fertiliser addition. This is problematic especially for P, since P fertilisers are made from rock phosphate (RP) and may have limited availability in the future due to their global resource distribution and depletion of global P reserves (Reijnders, 2014). In the context of a circular economy, alternative P fertilisers may include poultry manure, a waste material that is available in large quantity due to a growing broiler industry (FAO, 2018). This material may be recycled into soil amendments by composting to prevent environmental concerns. Indeed, poultry manure compost (PM) is a suitable fertiliser to improve yield and enhance soil physical properties and SOC sequestration (Li et al., 2011; Malik et al., 2013; Mierzwa-Hersztek et al., 2018; Mubeen et al., 2021; Poblete-Grant et al., 2019, 2020). To optimise resource use and to prevent adverse effects (e.g., contamination with heavy metals), combined application of PM and RP has been suggested (Mubeen et al., 2021; Poblete-Grant et al., 2019).

The use of organic or inorganic fertilisers may affect the functioning of plant and soil microbial communities differently because of contrasting nutrient availability and input of exogenous organic matter. Indeed, organic fertilisers were shown to increase root growth (Zhang et al., 2020) and labile SOC (Datta et al., 2010). Root-derived compounds together with available nutrients may be taken up and incorporated into the soil microbial biomass. The latter process was found to be a pre-exquisite for SOC stabilisation (Cotrufo et al., 2013). A recent study showed that different organic fertilisers alter root carbon input and its use by the soil microbial biomass (Vidal et al., 2020) and therefore most probably SOC sequestration. Accordingly, organic fertilisation strategies should be investigated in order to improve OC transfer from plant to soil. To the best of our knowledge, the effect of contrasting P fertilisers on these processes has never been assessed.

Therefore, in this study, we examined the influence of rock phosphate (RP), poultry manure compost (PM) and their mixture (PMRP) on OC transfer from plant to soil and allocation of plant-derived OC (root-derived OC) into particular SOC pools. To investigate the influence of edaphic properties on the general nature of the response pattern and its magnitude, we used two soil types differentiated by their P status and soil reaction. Our conceptual approach included continuous ^{13}C labelling of ryegrass plants grown on a Luvisol and a Neoluvisol in a growth chamber under controlled conditions, followed by destructive sampling and soil physical fractionation. We separated the unprotected OC fraction (FLf) from the one occluded in aggregates (OLf) and OC in organo-mineral associations (Hf). We quantified plant-derived OC, in the three different SOC pools with contrasting stability by using the isotope mass balance approach. We made two hypotheses: (1) in treatments with organic P fertilisers we will observe greater microbial biomass and more available nutrients than in those with mineral P fertilisers because of greater plant-derived OC input and (2) among the three P fertiliser treatments, we will observe contrasting plant-derived OC allocation to SOM fractions because of their specific effects on OC flow from plant to soil.

2. **Materials and Methods**

2.1 Materials

We used two soils differing in pH, available P (Olsen-P) and bulk density. Both soils belong to the French observatory SOERE PRO (https://www6.inra.fr/valor-pro/SOERE-PRO-les-sites) and were collected at 0-30 cm depth at Colmar (Eastern France) and Le Rheu (northwestern of France). They were classified as Neoluvisol (NEO) (pH 6.1) in Colmar, and Luvisol (LUV) (pH 8.5) in Le Rheu (Baize and Girard, 2008).

The NEO soil was characterised by a bulk density of 1.54 g cm^{-3} and an available (Olsen's) P concentration of 60 mg kg^{-1}. Total SOC concentration was 10 mg g^{-1}, and total N concentration was 1 mg g^{-1},. The soil had a silty texture with a clay content of 14.6 %. The LUV soil was characterised by a bulk density of 1.26 g cm^{-3} and an available (Olsen's) P concentration of 11 mg kg^{-1}. Its SOC concentration was 12 mg g^{-1}, and its N concentration was 1 mg g^{-}1. Additionally this soil contained 128 mg g^{-1} $CaCO_3$. The soil had a silty texture with a clay content of 20.7%.

Poultry manure (PM) had a P concentration of 13.2 mg g^{-1} , and a humidity of 22%. It showed a carbon concentration of, 288 mg g^{-1} OC, a nitrogen concentration of 45 mg g^{-1} total N, and a C:N ratio of 6.4. The mineral fertiliser phosphate (RP) showed a P concentration of 300 mg g^{-1} and a Ca content of 500 mg g^{-1} as CaO. It had a residual C content of 20 mg g^{-1}, 0.5 mg g^{-1} total N, and a C:N ratio of 45.9.

2.2 Growth chamber experiment

Perennial ryegrass (*Lolium perenne*) was grown in pots with 500 g of soil (unaltered or amended with organic and/or inorganic P fertilisers). The species was chosen because of its high yields and ease of establishment, making it a popular choice for permanent grasslands (Rivero et al., 2019). A total of 97 ryegrass seeds were sown in the pots containing the two different soil types. Organic and/or inorganic fertilization was applied in form of dry powder to match a P input of 100 mg P kg^{-1}. We had the following treatments: composted poultry manure (PM), rock phosphate (RP), a mixture of composted poultry manure and rock phosphate (PMRP), unfertilized soil (control), and. unplanted soil (bare soil). To account for the nutrient input from PM, N and potassium (K) in the control and treatments with RP were amended with NH_4NO_3 and KCl, respectively (262 mg N and 221 mg K per kg soil) to reach similar concentrations as in the PM treatment. PM addition was added based on its P content and corresponded to an application of 14- and 9.8-ton ha^{-1} in PM and PMRP treatments.. In addition, the OC inputs were 443 and 310 mg C g^{-1} from PM and PMRP respectively. The fertilization rate of RP was equivalent to 0.8 and 0.25 t ha^{-1} in RP and PMRP treatments.

We used a completely randomized factorial experimental design with four replicates per treatment and set up the experiment in a growth chamber (SERVATHIN Rubic V, iEES Paris, Thiverval-Grignon). Temperatures were 24°C and 17°C during the day and night, respectively. They were selected as optimal growth temperatures of temperate perennial ryegrass species, which ranges between 15 and 25°C (Perera et al., 2020). For the first 13 days, the light intensity was 650 mol m^{-2} s^{-1}, with a day length of 8 h and 11 h thereafter until the end of the experiment. Plant development took place over the course of three weeks in controlled soil moisture conditions. Moisture was monitored through the use of ten humidity probes (Decagon Echo 5) randomly distributed in the pots. It was maintained on average at 40% of the field capacity by regular watering. Twenty days after seeding (3 weeks), the growth chamber was artificially labelled during the following 4 weeks using continuous ^{13}C-CO_2 enrichment of the atmosphere (approximately 145 g of 10 atom-% ^{13}C-CO_2), leading to a mean ^{13}C ratio of 868‰ (standard error = 83). The pots were harvested 7 weeks after seeding when plants were at tillering stage. Shoots and roots were removed from the soil, washed with distilled water, and their fresh weight was determined. After oven drying at 65°C for 48 h the plant material was ground to pass a 0.84 mm sieve. The remaining soil was classified as rhizosphere soil and was oven-dried at 40°C and sieved at 2 mm. An aliquot of all samples was ground for further analyses.

2.3 Microbial biomass carbon

We used the chloroform fumigation-extraction method (Vance et al., 1987) to determine microbial biomass C (MBC) in 5 g of fresh soil. Briefly, fumigated and unfumigated soils were extracted with of $K_2SO_4^-$ and the TOC concentration of the extracts measured with a TOC analyser (TOC-VCSH by Shimadzu with a sampler ASI-V by Shimadzu).. The microbial biomass was determined using the difference between fumigated and unfumigated samples.

2.4 Soil organic matter density fractionation

Soil organic matter (SOM) was divided into three fractions by density fractionation using 20 g of soil and 25 ml polytungstate following a method proposed by Adams et al., (2018). We isolated the free light fraction (FLf), occluded light fraction (OLf), and the heavy fraction (Hf). The FLf and OLf fractions were overdried at 40°C, and the Hf fraction was freeze-dried. Thereafter, an aliquot was ground and analysed for elemental and isotopic composition.

2.5 Elemental and isotopic analyses

We determined the OC and N content of the bulk soil and physical fractions with an elemental analyser Variopyrocube (Elementar). Before the analyses, decarbonation of the LUV soil was carried out by HCl-fumigation (Harris et al., 2001). We used an Isotope Ratio Mass Spectrometer (Micromass Isoprime) to determine the stable carbon isotope composition of soil and plant material relative to the Vienna Pee Dee Belemnite (VPDB) international standard.. It was calculated as follows:

$$\delta^{13}C\,(\text{‰}) = (\frac{R_{sample}}{R_{standard})} \times 10^{3} \qquad (1)$$

where R = $^{13}C/^{12}C$ (molar ratio).

2.6 Calculations of the contribution of the two different carbon types (plants and poultry manure compost)

Plant-derived OC in soil,, which we hypothesised to be of root origin (RDC), was computed for bulk samples and density fractions from the natural $\delta^{13}C$ abundance by using the following equation:

$$RDC\ (\%) = \frac{(\delta^{13}\ OC\ treatment - \delta^{13}\ OC\ bare\ soil)}{(\delta^{13}\ enriched\ root - \delta^{13}\ OC\ bare\ soil}\ x\ 100 \quad (2)$$

where “$\delta^{13}C$ treatment” refers to all treatments sampled at the end of the experiment, “$\delta^{13}C$ bare soil” is the soil without plants, and “$\delta^{13}C$ enriched roots” is the mean $\delta^{13}C$ value of ryegrass roots of each treatment.

For the PM and PMRP treatment, poultry manure-derived OC (PMC) was estimated as the difference in total SOC following the treatments and the sum of the bare soil OC and root-derived OC (RDC) (Zhang et al., 2015). Additionally, RDC (mg) and PMC (mg) allocated in each SOM fraction was calculated similarly by using the mass balance.

2.7 Data analysis

The data sets were checked for normality (Shapiro-Wilk test) and homogeneity of variance (Levene test). Statistical differences of means (95% significance level) were analysed using analyses of variance (ANOVA). We tested the factors: soil type (S), treatment (T) and their interaction (S x T). Post hoc tests with the function Tukey-test were made for the explanatory variables independently when the ANOVAs detected significant differences. The relationships between soil physicochemical parameters (Poblete-Grant et al., 2019) were tested by Pearson correlation analyses. Furthermore, a multiple linear regression model was performed by selecting manually predictors from the full model to generate a simplified model. Models were checked for normality and homogeneity using “nortest” and “lmtest” packages. Furthermore, collinearity was tested using the “vif” function from the “car” package. Models were selected based on the their R value the Akaike criterion (AIC). Finally, we performed a principal component analysis to identify the response variables that best explained the treatment and soil type effect using the “facto-extra”, “devtools”, and “ade4” packages. The statistical software R Foundation for Statistical Computing Version 3.6.3 was used to conduct the tests (R Development Core Team 2009-2018 RStudio, Inc). Effects were declared significant at $p \leq 0.05$.

3. **Results**

3.1 Elemental content and stable isotope ratios of plant tissues and soils amended with different fertiliser types

Plant OC concentration ranged from 334 to 410 mg g^{-1} for shoots and from 153 to 355 mg g^{-1} for roots (Table 1). Shoot and root OC were lower for plants grown on LUV soil compared to those grown on NEO soil (Table 1). In addition, root OC content significantly increased after PM and PMRP amendment of both soils. Plant N concentrations ranged from 16.2 to 58.7 mg g^{-1} in shoots and from 5.52 to 18.4 mg g^{-1} in roots (Table 1). The nitrogen concentrations of shoots of plants grown on the LUV soil were significantly increased by RP followed by PMRP. However, root N concentrations were lowest in the RP treatment (Table 1). When grown on the NEO soil, shoot and root N concentrations were most increased by RP followed by PM and PMRP. The C:N ratios ranged from 5.80 to 24.8 and 13.9 to 28.1 for shoots and roots, respectively. Soil type influenced C:N ratios of shoots and roots, being higher when plants were grown on the NEO soil as compared to the LUV soil. The PM and PMRP amendments increased the C:N of roots for the LUV soil, while it was decreased for the NEO soil (Table 1). When RP was added to both soils, shoot C:N ratio decreased. The stable C isotope ratio ($\delta^{13}C$) ranged from 940 to 1,078 for shoots and from 611 to 1,047 for roots (Table 1). It was similar for controls, PM, and PMRP treatments of both soils. The $\delta^{13}C$ of shoots was highest for plants grown on the LUV soil amended with PM and PMRP, whereas for plants grown on the NEO soil, RP and PMRP treatments showed the highest $\delta^{13}C$ followed by PM and control. The root $\delta^{13}C$ was increased only in the RP treatment of the NEO soil (Table 1).

Insert Table 1, please

The total SOC concentrations ranged between 10.5 and 16.5 mg g^{-1} (Table 1). PM amendment led to significantly increased SOC values in both soils, whereas PMRP addition increased SOC only in the NEO soil (Table 1). Soil N concentrations ranged between 1.22 to 2.01 mg g^{-1} and were significantly increased only in the NEO soil by using PM. On the other hand, soil C:N ratios ranged from 7.7 to 8.9 and were lowest for the NEO soil amended with RP (Table 1). Soils differed in $\delta^{13}C$, being higher in the NEO soil as compared to the LUV soil (Table 1). The $\delta^{13}C$ increased in the LUV soil by using PM and PMRP. However, for the NEO soil, RP and PMRP treatments showed the greatest $\delta^{13}C$. The RP treatment showed lower $\delta^{13}C$ for the LUV soil as compared to the NEO soil.

In addition, soil type and treatments significantly affected root-derived OC (RDC) input ($p \leq 0.001$; Table 1). It ranged from 0.11 and 6.67% corresponding to …. And … mg in all treatments (Table 1). RDC input was higher in the NEO than the LUV soil. The PM and PMRP treatments increased RDC in both soils as compared to the control and RP treatments.

3.2 Microbial biomass, and elemental content of SOM pools as influenced by fertiliser types

Microbial biomass carbon (MBC) ranged from 102 to 484 mg kg^{-1}. It showed significant differences for soil type, treatment, and their interaction (p≤0.001; Fig. 1; Table S2). We found that the application of PM significantly increased MBC in the LUV and NEO soils, with regards to the control. The RP treatment had a negative effect on MBC leading to lower values (14–38%) for both soils as compared with the unfertilised control. However, combination of RP with PM induced the greatest MBC increases (2-fold) for the NEO soil. In the LUV soil amended with PMRP, similar MBC concentrations as in the control were recorded.

Insert Figure 1, please

3.3 SOC concentrations and distribution in physical fractions

The SOC concentrations of the FLf fraction ranged between 147 to 237 mg g^{-1} (Table 2). They were lower than the SOC concentrations of the OLf fraction and higher than those of the Hf fraction, ranging between 206 to 328 mg g^{-1} and 7.61 to 12.2 mg g^{-1}, respectively. Treatments showed significant differences for the SOC concentration of the FLf, OLf, and Hf fractions (p≤0.01; Table 2), while only the SOC concentration of the OLf fraction showed differences according to soil type (p≤0.001; Table 2). The interaction between soil type and treatment was significant for the SOC concentration of the FLf fraction (p≤0.001; Table 2).

Total N concentrations ranged from 8.60 to 20.1 mg g^{-1} in the FLf and from 11.6 to 26.2 mg g^{-1} in the OLf fractions. They were strongly increased by PM and PMRP addition in both soils (Table 2). In the Hf fraction total N concentrations ranged from 1.01 to 1.33 mg g^{-1} and showed no differences between treatments.

The C:N ratio ranged between 12.4 to 19.3 in the FLf and between 11.8 to 16.2 in the OLf (Table 2). The FLf and OLf of the PM and PMRP treatments showed the lowest C:N ratios. On the other hand, the C:N ratio of the Hf ranged between 7.61 to 12.2 with no differences among the treatments.

The allocation of SOC to FLf was increased from 9% to 20 and 14% in the LUV soil amended with PM and PMRP, respectively (Fig. 2A). Interestingly, RP reduced the SOC allocation to the FLf of the LUV soil. On the other hand, the allocation of SOC to the OLf of the LUV soil was slightly increased by PM and PMRP as compared to RP and control,. In the NEO soil, the allocation of SOC to the FLf was increased from 15% to 31 and 27% by the PM and PMRP, respectively.

3.3 The allocation of plant and poultry manure compost-derived OC to SOM fractions is depending on the fertiliser type

PM and PMRP treatments increased RDC contribution to both soils, compared to the control soil, while RP treatments showed no change. In the FLf, RDC contribution ranged from 3.66% to 17.6%, and was highest in PM and PMRP treatments (Table 2). In RP treatments, values were similar as those of the control. RDC allocated to the OLf, was lower, varying between 1.18 and 6.56% (Table 2). The PM treatment showed the highest RDC in the OLf of the LUV soil, while PMRP showed the greatest RDC in the OLF of the NEO soil. In the Hf fraction, RDC accounted for 2.09 to 5.82% (Table 2). It was higher than the control in the PM treatment and lower than the control in the RP treatment for the NEO soil, while in the LUV soil only PM treatment showed significantly higher values than the control.

Insert Figure 2, please

The total quantity of poultry manure-derived OC (PMC) was higher in the PM treatment (3.03 and 7.82 mg) as compared to PMRP (1.43 and 5.04 mg) in both soils (Fig. 3A). In PM and PMRP treatments of the NEO soil, highest amounts of PMC were found in the FLf (47.7 and 26.9 mg) followed by the Hf (24.4 and 19.3 mg), and finally in the OLf (4.31 and 2.11 mg) (Fig. 3B-D). In contrast, the LUV soil showed differences of PMC allocation in these two treatments. The PMC in the LUV soil amended with PM was mainly accumulated in the FLf (18.8 mg) and in the Hf (16.0 mg), and the less PMC was found in the OLf (1.50 mg). However, PMRP treatment showed the highest accumulation of PMC (43.7 mg) in the Hf as compared to the PM treatment (16.0 mg) (Fig. 3D). Moreover, in the LUV soil amended with PMRP, the accumulation of PMC was highest in Hf followed by FLf (8.02 mg), and finally in the OLf (1.10 mg) (Fig. 3D). Total PMC and PMC allocated in the FLf were significantly affected by soil type, treatment, and their interaction ($p \leq 0.01$; Table S2). We also observed significant differences for the PMC allocated to the OLf and Hf due to the treatment ($p \leq 0.001$; Table S2).

Insert Figure 3, please

3.4 Relationships between RDC allocation to physical fractions and biological and physicochemical parameters

The multiple linear regression models showed that readily available organic P was the explanatory variable with the greatest positive effect on the contribution of RDC in all SOM fractions of both soils (Table 3). MBC and MBP also contributed to the development of these models. In the LUV soil, the readily available organic P and MBP explained the 89% of the variability of RDC in the FLf, while in the NEO soil both variables explained the 76% and 69% of the variability of RDC in the OLf and Hf. The readily available organic P and MBC predictors, on the other hand, explained 66% and 94% of the variability of RDC in the OLf and Hf of the LUV soil, respectively, as well as 96 of the variability of RDC in the FLf of the NEO soil (Table 3). For the OC-FLf, the variables RDC-FLf and PMC-FLf explained the 72% and 74% of its variability. In the NEO soil, readily available organic P explained 54% and 64% of the variability of OC-

FLf and OC-OLf, respectively. However, MBC and RDC-OLf were the variables, which were most important and explained (78%) the variability of OC-OLf (Table 3).

Insert Table 3, please

4. Discussion

4.2 Soil microbial biomass is enhanced by organic P fertilisers though substrate provision and stimulation of plant-derived organic matter input

Our findings showed that poultry manure compost fertilisation increased MBC in both amended soils (Fig. 1), which is consistent with the findings of Malik et al. (2013), who investigated two alkaline soils (pH 8.3) and Mierzwa-Hersztek et al. (2018), who studied a moderately acid soil (pH 6.4) amended with PM. On the other hand, we found that RP amendment of both soils decreased the MBC compared to the unfertilised control (Table 2). Similar negative fertiliser effects on soil microorganisms have previously been reported (Lupwayi et al., 2005). According to He et al. (1997), the primary mechanism responsible for the decreased MBC following RP amendment may be a rise in soil pH caused by liming materials containing CaO such as RP.

Stimulation of MBC by organic fertilisers may be related to high plant-derived OC input resulting from increased root biomass following the enhancement of the availability of both inorganic and organic P by PM amendment (Poblete-Grant et al., 2019). Thus, MBC increase might be explained by either, i) the enhanced availability of P and other nutrients, which allowed for higher root carbon input in the active SOM pool (FLf) or ii) a direct input of PM (Fig. 3), which could provide a readily available OC-source and thus stimulate MBC (Li et al., 2018; Lupwayi et al., 2019). It may also increase the available macronutrients inputs, which may be benefitting MBC (Mierzwa-Hersztek et al., 2018; Spohn et al., 2013). Soil microorganisms and SOM account for more than 10% of the plant-derived OC input belowground.

Microorganisms in the rhizosphere, whether alive or dead, may serve as a significant sink for root carbon and promote the development of soil microstructures (Vidal et al., 2018). Plants rely on soil microorganisms like bacteria and fungi to depolymerize and mineralize organic nutrient forms for their nutrient uptake (Jacoby et al., 2017). Due to a lack of readily available substrates, a large number of soil microorganisms may not be active. The readily accessible OC produced by roots most likely drives microbial activity and growth in the rhizosphere, resulting in the production of extracellular enzymes and, as a result, improved SOM decomposition and nutrient mineralisation (Kuzyakov and Xu, 2013). In these conditions, microbial biomass can compete for nutrients with plants. Microbial P and N uptake can prevent P fixation by soil colloids or N leaching. When the readily available OC is depleted, microbial biomass N and P become available to plants through microbial turnover. Microorganisms can thus be conceptualised as slow-release fertilisers that store P and other nutrients when their concentrations are high, and then release them when nutrient concentrations are low (Malik et al., 2013).

In addition, we found that MBC was greatly affected by soil type. For example, the LUV soil amended with PM showed the highest increase in MBC as compared to the control (Fig. 1), whereas in the NEO soil, the MBC for the PM treatment was lower than in the combined treatment PMRP. Malik et al. (2013) also found differences of MBC associated to soil type responses to PM amendment. These findings were attributed to contrasting soil texture and organic matter content. However, in our experiment, the two soils had comparable organic matter content and soil texture, but they differed in pH and initial available P status. Therefore, soil reaction and nutrient availability may have affected microbial growth response to the amendments. Furthermore, it was previously observed that RP was inefficient to promote belowground growth (Poblete-Grant et al., 2019), which might diminish the release of easily available OC from roots needed to increase the abundance of soil microorganisms.

4.3 Organic fertilisers improve carbon transfer from plant to soil organic matter fractions

Our study shows differences of root-derived organic carbon (RDC) contribution among soils and treatments (Table 1 and 2). Our results indicated that organic fertilisers, such as poultry manure alone (PM) or combined with rock phosphate (PMRP) were able to improve RDC similarly in both soil types.This is in contrast to mineral fertilisers in form of rock phosphate (RP) . Our findings are consistent with the results of Qiao et al. (2017) and Dou et al. (2016a, b), who found that pig manure can stimulate rhizodeposition by increasing nutrient availability in several soil types. According to their findings higher nutrient availability increased CO_2 fixation via photosynthesis, root biomass, and nutrient status in plants.,. This agrees with the contrasting contribution of RDC reported for the NEO and LUV soils, which might be related to their contrasting initial P availability. These results are in agreement with previously reported differences in ryegrass-derived OC as influenced by soil type (Domanski et al., 2001; Kaštovská and Šantrůčková, 2007; Kuzyakov et al., 2001). Indeed edaphic factors such as soil available P, N and pH may influence SOC dynamics and allocation to stabilised pools (Di et al., 2018).

Our results showed a higher allocation of RDC to the FLf and OLf fractions of soils amended with PM and PMRP compared to those amended with RP (Table 2 and Fig. 3B). The FLf is known as the active SOM pool, while the Hf is generally regarded as the mineral-associated and thus stabilised SOM pool (Von Lützow et al., 2007). Moreover, both soil types amended with PM showed an increased RDC contribution to OLf (Table 2). This fraction consists of partly decomposed organic matter occluded in soil aggregates (Adams et al., 2018; Wagai et al., 2009) providing physical protection and thus limiting OC availability for microbial decomposition (Rasse et al., 2005). Accordingly, previous data stated that long-term application of PM may increase SOC accumulation by its positive effect on soil aggregate formation (Poblete-Grant et al., 2020). In the Hf pool we found that the content of RDC was more increased in LUV and NEO soil amended with PMRP as compared with RP amendment and the unfertilised soil (Table 2). In general, RDC allocation in the three SOM pools was strongly influenced by the treatments containing PM; however, the two soil types showed differences betweenamong FLf and either OLf or Hf.

The positive effect on RDC allocation to the SOM fractions could be explained by the enhancement of soil organic P belonging to the readily fraction (extracted with H_2O and $NaHCO_3$). Multiple linear regression models supported our findings, which showed that readily available organic P coupled with MBC or MBP explained from 66% to 96% of the variability of RDC from all SOM fractions in both soils (Table 3). Therefore, we suggest that short-term organic fertiliser application may improve SOC storage in all SOM fractions due to their organic P input. This is in line with a recent literature review by Spohn (2020), who showed the importance of organic P for SOC storage, indicating that large amounts of P are required to achieve high levels of SOC accumulation promoted by initiatives such as 4 per mille (Soussana et al., 2017).

In contrast, RP did not promote the transfer of RDC to SOM fractions even though in our previous study showed an increase of root biomass in the NEO soil (Poblete-Grant et al., 2019). We found that RP addition decreased RDC in the Hf of the LUV soil, and in all fractions from the NEO soil as compared to their unfertilised control (Table 2). Thus, application of organic fertilisers may support both crop yield as well as SOC sequestration through direct OC input and the stimulation of plant growth by nutrient and OC input (Zhao et al., 2020).

Moreover, soil structure through aggregate stability induced by PM could play an important role in SOC dynamics (Poblete-Grant et al., 2020). Accordingly, the increased accumulation of poultry manure-derived OC (PMC) in the OLf fraction could be associated to its physical effect on enhancing soil macroaggregates. Differences in PMC content between soils, on the other hand, may be attributed to differences in soil mineralogy (Fig. 3). Accordingly, the high pH and concentration of $CaCO_3$ in the LUV soil could explain the high allocation of PMC in the Hf of the PMRP treatment highlighting the role of Ca from carbonates in the mineral bonds and interactions between minerals and SOM mediated by cation bridges (Zhang et al., 2016).

In general, P fertiliser types greatly influenced the contribution of plant-derived carbon and its allocation to SOM pools. Our study highlighted the important role of the soil biomass in the soil transfer of plant derived OC. Moreover, our study indicated that the availability of organic P might promote the release of root derived OC improving its incorporation to soil. We conclude that depending on soil type, the short-term application of poultry manure or its combination with rock phosphate as P fertiliser could represent an interesting alternative to stimulate plant- and poultry manure compost-derived carbon transfer to stabilised SOC fractions. The general pattern of these effects was less influenced by soil type than their magnitude Organic fertilisers may have beneficial effects on (1) the soil microbial biomass, crucial to ensure OC transfer from plant to soil and (2) biomass production. . Field trials are required to determine the effects of poultry manure alone and its combination with rock phosphate under real-world conditions in order to assess the long-term importance of these mechanisms.

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Author’s contributions CR, MLM, PB and PPG designed the experiment. PPG and PB carried out the experiment. PPG, CR, MLM analysed the data and wrote the manuscript. CR, MLM, PC, and SP reviewed the manuscript.

Declarations

Conflict of interest The authors mentioned that they do not have any financial or non-financial conflict of interest, and that this article does not contain any studies with human participants or animals.

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