

Soil organic matter stabilization at the pluri-decadal scale: Insight from bare fallow soils with contrasting physicochemical properties and macrostructures



Remigio Paradelo ^{a,*}, Folkert van Oort ^b, Pierre Barré ^c, Daniel Billiou ^a, Claire Chenu ^{a,1}

^a AgroParisTech, UMR 7618, BIOEMCO UPMC/CNRS/ENS/UPEC/AgroParisTech/IRD, F-78850 Thiverval-Grignon, France

^b INRA/AgroParisTech, UMR 1402 ECOSYS, Équipe Ecotoxicologie, RD-10, F-78026 Versailles Cedex, France

^c CNRS-ENS, Laboratoire de Géologie, PSL Research University, 24 rue Lhomond, 75005 Paris, France

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ABSTRACT

Physical protection is recognized as one of the main processes governing soil organic matter stabilization, but its importance over long time scales (decades to century) is being discussed. In this work, we used data from a long-term bare fallow experiment initiated in 1928 in Versailles (France) to investigate such process: given that no organic carbon inputs occurred since 1928, all the organic matter present had pluri-decadal to centennial mean residence times. The annual addition of mineral amendments (CaCO₃ or KCl) produced contrasting superficial soil structures in some plots compared to non-amended plots. We hypothesized that a more aggregated and stable soil structure would likely be associated with higher organic carbon stocks. Stability of soil structure was quantified using three complementary tests: slow wetting to study macroaggregation, moderate dispersion compared to strong dispersion to study microaggregation. The CaCO₃ plots had the highest macroaggregate stability, and KCl plots the lowest but microaggregation at the silt-size scale was similar for the three soils. After 79 years of bare fallow soil organic carbon stocks in the bulk soil were about 25% higher in the CaCO₃ plots than in the KCl and reference plots. This relative increment was due to a higher amount of silt and clay-associated soil organic matter in CaCO₃ plots, as a consequence of better physical or physicochemical protection at these scales, with a less important role of physical protection within stable macroaggregates.

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1. Introduction

Among different soil organic matter (SOM) pools, one was demonstrated to be hundreds to a thousand years old by means of ¹⁴C measurements (Trumbore, 1997; Jenkinson et al., 2008) and long term C3/C4 vegetation changes (Balesdent et al., 1988). This pool is often referred to as “stable”, due to its low turnover rate. A number of mechanisms have been proposed to account for the stabilization of organic matter against its natural tendency to be mineralized by microorganisms, such as physical and physicochemical protection (Christensen, 1996; Kögel-Knabner et al., 2008). However, it is not easy neither differentiating between these processes, nor isolating such a stable pool of SOM. Consequently, there is a lack of knowledge concerning both the processes of stabilization and the methods for quantifying C with residence times of decades to centuries.

Basically, “physical protection” is due to the spatial disconnection between organic matter and microbial decomposers or to unfavourable

physicochemical conditions in the habitat of microorganisms (Balesdent et al., 2000; Chenu and Stotzky, 2002). These processes may operate at different spatial scales. In the search for sites of SOM physical protection, macroaggregates (>250 μm) were first shown to protect SOM (e.g. Beare et al., 1994), then the role of sand-sized microaggregates (53–250 μm, especially if located within stable macroaggregates, Six et al., 2000), and of silt-sized microaggregates (2–50 μm, Virto et al., 2010) were highlighted. Recent research focused on SOM occlusion in very fine-sized (<2 μm) aggregates (Chenu and Plante, 2006).

For studies on SOM with mean residence times of decades to centuries, long-term bare fallow experiments, kept continuously free of vegetation, are very useful. Under such conditions, C inputs from plants have been stopped for a long time and SOM mineralization proceeds without interferences. Thus, it can be expected that labile SOM pools will degrade first and SOM will become progressively enriched in more stable SOM. In agreement with this hypothesis, Barré et al. (2010) found that the soils at the 80-years old long-term bare-fallow experiment of Versailles (France) currently contain almost exclusively C with a turnover rate of more than a century.

Long-term bare fallow sites offer exceptional conditions to investigate the factors and processes explaining SOM stabilization at the scale of decades to centuries. In the 42-plot long-term bare fallow

* Corresponding author at: Universidade de Vigo, Departamento de Bioloxía Vexetal e Ciencia do Solo, Facultade de Ciencias de Ourense, As Lagoas s/n, 32004 Ourense, Spain.

E-mail address: remigio.paradelo@uvigo.es (R. Paradelo).

¹ Present address: AgroParisTech, UMR 1402 ECOSYS, INRA/AgroParisTech, F-78850 Thiverval-Grignon, France.

experiment of Versailles, annual application of different chemical fertilizers, organic and alkaline amendments was performed since 1928 (Burgevin and Hénin, 1939) and compared with plots without any addition. These practices have led to the development of contrasting physicochemical properties and soil structure in the surface layer (van Oort, 2013). In plots receiving CaCO_3 or CaO , a well-developed aggregated soil structure is observed, whereas in plots under potassium salt applications soil structure rapidly collapses after rain events (Bresson and Boiffin, 1990; Pernes-Debuysse and Tessier, 2004; Paradelo et al., 2013). Such different soil structures are likely the consequence of direct and indirect effects of the amendments, such as pH and cation composition, which affect aggregate stability.

The experimental conditions of long term bare fallows allow to decouple the processes of C input and soil aggregate formation, which usually operate together in soils. This work aimed at examining the following hypothesis: if SOM is protected from biodegradation within stable aggregates, then the plots with a well-developed aggregated soil structure (in our case under Ca-based amendments) should present larger soil organic carbon (SOC) stocks than those with a poorly aggregated structure (under K salts) after 80 years of bare fallow use. For testing this, we selected plots with contrasted structures, measured their SOC stocks and characterized their structure and aggregation by using a complementary series of aggregate dispersion methods with increasing disruption energy.

2. Material and methods

2.1. The Versailles long-term bare fallow

The 42-plot long-term bare fallow of Versailles was established in 1928 by the Institut National de la Recherche Agronomique (INRA) in the gardens of the 'Chateau de Versailles' (France). At that time, the objectives were to study impacts of continuous application of different chemical fertilizers and amendments on the composition and physical properties of soils without the influence of crop inputs (Burgevin and Hénin, 1939). The site is located in the Paris Basin, with a mean annual temperature and precipitation of 12.4 °C and 700 mm, respectively. The soil is a silty loam Haplic Luvisol (IUSS Working Group WRB, 2006) developed in aeolian loess, characteristic for large regions in north-western Europe. The experiment consists of 42 plots (2 × 2.5 m) managed under bare fallow. All plots are turned over with a spade, twice a year (spring and autumn) to a depth of 25 cm, and kept free from vegetation by hand weeding and herbicide treatment. The treatments assayed in the 42 plots of the experiment are described in detail in Paradelo et al. (2013). They include 16 duplicated applications of a variety of the main fertilizers of N, P and K, different basic and organic amendments, as well as 10 reference plots without treatment. Soils of the plots have been sampled during the 80 years resulting in a large historical sample archive (van Oort, 2013).

We selected plots with most contrasting soil surface structure, under applications of KCl (plots 23 and 37, receiving an equivalent rate of 150 kg $\text{K}_2\text{O ha}^{-1} \text{yr}^{-1}$), and CaCO_3 (plots 31 and 39, receiving an equivalent rate of 1 Mg $\text{CaO ha}^{-1} \text{yr}^{-1}$), as well as three reference plots (plots 22, 30 and 34, no amendment). This makes a total of two replicates per treatment for the KCl and CaCO_3 treatments and three replicates for the control. Although not an ideal situation for statistical processing, we are hampered by the original design of the experiment. The samples studied in this work (Fig. 1) were collected in April 2008, i.e. 80 years after the beginning of the experiment, before spring soil digging. Three intact soil cores with a known volume were collected at 0–20-cm depth per plot. Samples were air-dried and stored in sealed desiccation flasks prior to analyses.

2.2. General analyses

Bulk density (BD), pH, total organic carbon (TOC) and total N, were determined on all samples. Bulk density was determined directly on

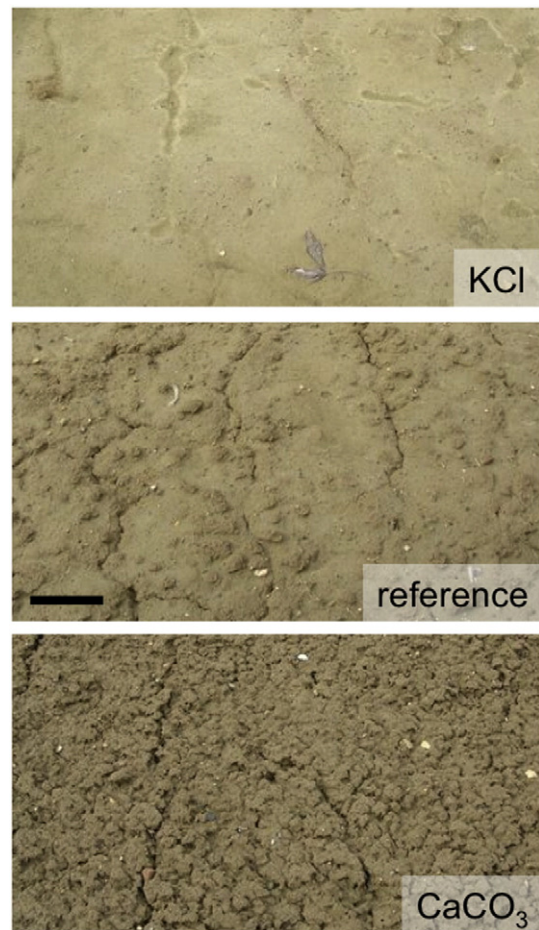


Fig. 1. Aspects of the surface macrostructure of the plots studied. All photographs are at the same scale; the black bar represents 20 cm (Photos: C. Chenu).

the soil cores. The pH was measured in a 1:2.5 soil:water extract, according to NF ISO 10390 (AFNOR, 2004). For TOC and N analysis, the bulk soil samples were dried at 105 °C for 48 h, milled to a homogeneous powder (<0.2 mm) and then stored in desiccators until required for analysis. TOC and N concentrations were measured by dry combustion in a CHN autoanalyser (Carlo Erba NA 1500). The carbonate fraction of the samples from the CaCO_3 plots was removed by exposure to concentrated HCl vapour under a glass desiccator, 6 h at room temperature (Harris et al., 2001).

SOC stocks were calculated using the equivalent mass approach (Ellert and Bettany, 1995), based on bulk density and TOC data. The CaCO_3 plots had the lowest bulk density and the weight of the upper 20 cm reached 245 kg m^{-2} . For a valid comparison, the OC stocks of the other plots were compared on the base of comparable 245-kg m^{-2} weight. Additionally, samples from 1929, 1939, and 1962 were selected from the historical soil archive and analysed for their total OC and N contents as described above.

2.3. Assessing soil aggregation

Three methods offering increasing dispersive energies were employed for obtaining insight into aggregate stability.

Macroaggregate stability was assessed by using the slow wetting test under controlled tension (Le Bissonnais, 1996), assumed to mimic soil rehydration by gentle rain in field conditions. It is less destructive than fast wetting and allows better discrimination between unstable (0.4 mm < MWD < 0.8 mm) and very unstable (MWD < 0.4 mm) soils (Le Bissonnais and Le Souder, 1995). Briefly, five grams of 3.15–5 mm aggregates were placed on filter paper on a tension table and

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