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Geological control of soil organic carbon and nitrogen stocks at the landscape scale

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ABSTRACT

Parent material can deeply influence soil organic matter (SOM) stocks. In this study we tested the hypotheses that parent material had an effect on SOM concentrations and stocks and that this effect may be explained by the influence of soil parent material on basic soil parameters. However, as the factors known to influence SOM stocks such as land use and climate frequently co-vary with geology, testing the influence on SOM stocks of the factor "soil parent material" alone is challenging.

To properly test our hypotheses, we studied SOM stocks of forest and cropland soils in a small landscape (17 km^2) of the Paris basin (France), *i.e.* with an homogeneous climate. We collected topsoil samples (0–30 cm) in 50 forest and cropland plots, located in five geological contexts: loess deposit, mudstone, grainstone, chalk and calcareous clay deposits. Basic soil parameters (texture, pH, $CaCO_3$ concentration) and SOM stocks to 30 cm depth (organic C and total N) were determined on the 50 soil samples.

Organic C and total N concentrations and stocks in topsoils (0–30 cm) were much higher in forests than in cultivated soils (38.1 (±12.8) *vs.* 19.0 (±4.7) g C kg^{-1} soil and 83.4 (±19.8) *vs* 48.9 (±9.9) t C ha^{-1} for SOC concentrations and stocks respectively). The influence of land-use on organic C and total N concentrations and stocks was modulated by parent material (significant interactions between land-use and parent material, $p < 0.05$ for concentrations and stocks). Indeed, the difference in organic C and total N concentrations and stocks in topsoils (0–30 cm) was much lower for soils developed on loess deposits.

While SOC concentration was significantly correlated to soil clay concentration for both cropland ($r^2 = 0.36$, $p < 0.001$) and forest ($r^2 = 0.44$, $p < 0.001$), there was no significant relation between SOC stocks and soil clay stocks for forest soil ($p = 0.11$) and a significant but highly scattered positive correlation between SOC and clay stocks in cropland soils ($r^2 = 0.20$, $p = 0.02$). No significant relation between pH or $CaCO_3$ and SOC stocks was observed. Our results therefore revealed that soil parent material can significantly influence topsoil (0–30 cm) organic C and N stocks but that more research is needed to understand how soil parent material influences SOM stocks as it cannot be simply explained by basic soil physico-chemical parameters (clay and carbonate concentrations or stocks, pH). Overall, our results suggest that a good knowledge of the geology is needed to better constrain SOC stocks as well as SOC stocks evolution in a changing environment from landscape to global scale.

1. Introduction

Soil organic matter contains about three times more C than the atmosphere and it has been recognized that small changes of soil organic matter (SOM) stock can have a significant impact on atmospheric greenhouse gases concentration (CO_2, CH_4 and N_2O) at a decadal timescale (Johnson et al., 1995; Eglin et al., 2010).

Soil parent material can have a major impact on ecosystem (vegetation and soil) functioning (Jenny, 1994) and therefore deeply influence SOM stock. Soil parent material has been observed to be an important driver of SOC and N stocks at the regional scale (Heckman et al., 2009; Baritz et al., 2010; Wilson et al., 2011; Wiesmeier et al., 2013; Prietzel and Christophel, 2014; Johnson et al., 2015; De Vos et al., 2015). However, in such studies, several factors influencing SOM stocks, such as climate or land-use, are often co-varying with the parent material. As a result, the effect of soil parent material on SOC and N stocks cannot be clearly established from this kind of studies (Wiesmeier et al., 2013). To do so, it would be necessary to elaborate a specific sampling design

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that would allow investigating SOM stocks in different geological conditions experiencing the same land-use and climatic conditions. This is the aim of this study conducted at the landscape scale.

Land-use strongly impacts SOM stocks (Guo and Gifford, 2002; IPCC, 2006). In particular, numerous studies showed that tilled cropped soils have on average lower SOM stocks compared to forest or grassland soils (*e.g.* Poeplau and Don, 2013). This may be explained by the lower C inputs in cropped fields but also by the disruption of soil aggregates due to tillage leading to a higher mineralization of particulate organic matter (POM) protected within aggregates (*e.g.* Balesdent et al., 2000). The influence of a land-use change on C inputs or POM mineralization could also be a function of soil parent material. One can therefore expect that the SOM stock modification following a land-use change is modulated by soil parent material.

This study aimed at evaluating the effect of soil parent material (*i.e.* lithology) on SOM stock (SOC and N stocks) under two land-uses (forest and cropland). To do so, 50 plots (5 different geological conditions × 2 land-uses × 5 replicates) were sampled in a small (17 km^2) landscape of the Paris basin (France). This area had a quadruple benefit to study the influence of geology on SOM stocks: (1) an available detailed geological mapping; (2) a short distance variation of geological conditions; (3) an almost homogeneous climate; (4) plots with contrasted land-uses for the different geological conditions. This experimental design allowed testing the following hypotheses: (1) soil parent material influences SOM stocks; (2) SOM stock differences between cropped and forested plots are modulated by soil parent material.

2. Material and methods

2.1. Choice of geological conditions, land-uses and sampling sites

The study area was located in and around the AgroParisTech domain (Thiverval-Grignon, Yvelines, France; 48°51′N – 1°55′E). Mean annual temperature and precipitation are respectively 10.7 °C and 649 mm across this small landscape (17 km^2). A detailed (1:25,000) geological map of the landscape has been established. From the geological map, five different soil parent materials were selected: loess deposit, mudstone, grainstone, chalk and calcareous clay deposits. The selection criteria were (1) homogeneity of the soil parent material (colluvial soils were thus excluded); (2) wide area covered in the domain or (3) particularly interesting soil properties (clay deposits). Typical profiles of the soils developed on the five selected geological conditions are presented in Fig. S1. The soil developed on loess deposit is classified as a Luvisol and the soils developed on the other soil parent materials are all classified as Cambisols (WRB, 2014).

Two land-uses were selected, cropland and forest, given their quantitative importance in the study area. Forest sites (oak-hornbeam or oak-ash forests) were all old forests (established since at least 1820) located within the park of the AgroParisTech domain. Cropland sites were located in fields belonging to or exploited by local farmers, AgroParisTech or INRA. All cultivated plots have been used as cropland for at least two centuries and were conducted with similar cropping systems, *i.e.*, conventional management for several decades, characterized by rotations based on cereals (other crop being rape), an annual tillage to 30 cm depth, mineral fertilization and exports of cereals straw. Fields conducted under no-tillage management and fields receiving intensive application of sewage sludge were excluded. The application of mineral fertilizers was not standardized in the choice of the cultivated plots to be sampled but were not specific to the soil parent material.

Soil and vegetation maps were superposed using ArcGIS©. For each couple [parent material × land-use], 5 replicates were sampled. The different sampling sites were considered as independent, as soils taken from croplands were sampled from different agricultural plots and soils taken from forests were sampled at least 70 m away from each other.

2.2. Soil sampling protocol

Samples were collected in spring 2013. At each sampling location, plants and/or litter were gently removed from the surface before sampling. The sampling depth was set to 30 cm in all cases for different reasons: (1) it was a mean to standardize soil sampling; (2) it allowed comparisons with other studies, often focused on the top 30 cm (*e.g.* Martin et al., 2011); (3) for croplands, 30 cm was the historical tillage depth even if it tends to be reduced nowadays; (4) a significant portion of soil organic carbon is stored in the top 30 cm, especially for most soils developed on mudstone, grainstone and chalk which were shallow soils (25–30 cm depth on average) across the study area. However, deep carbon represents >50% of the global soil carbon stocks (Jobaggy and Jackson, 2000), which possibly applies to the soils developed on loess of the AgroParisTech domain.

Soils were sampled with a clean hand auger in two steps (0–20, 20–30 cm). When the auger touched the underlying bedrock before a 30 cm depth, sampling was stopped and the depth noted down. Five subsamples were collected (one central sample and four others three meters away from it in the four cardinal directions) and mixed by hand in a plastic tray. All visible living organisms were removed. A soil core (0–30 cm) was additionally sampled with a cylindrical auger to allow for bulk density estimate. Immediately after returning to the lab, soil samples were put in clean plastic trays, crumbled by hand to facilitate further sieving and left to dry at room temperature until they reached a moisture of approximately 10% *w*/w. After a few days (depending on their moisture on sampling day), they were forced through a 2-mm sieve, dried at 60 °C and bagged. Rocks and gravels larger than 2 mm were disregarded and further analyses were performed on fine earth (<2 mm) fractions.

2.3. Bulk density measurements

The topsoil (0–30 cm) samples kept aside for bulk density estimates were weighed and dried at 105 °C. Once dry, they were wet sieved at 2 mm. Coarse (>2 mm) and fine earth (<2 mm) materials were dried at 105 °C and weighed. Soil bulk density was obtained by dividing the mass of fine earth soil (without coarse elements) by the volume of the soil core (taking into account the actual core length for soils that were shallower than 30 cm).

2.4. Soil parameters measurements

Topsoil (0–30 cm) texture was determined on *ca.* 10 g of dry soil by combined sieving and sedimentation after OM oxidation with hydrogen peroxide and particle dispersion using sodium hexa-meta-phosphate (5 g L^{-1}). The pH of topsoil samples was determined with a glass electrode in the supernatant of a soil suspension using a 1:5 (*w*/*v*) mixture of soil and water. Total $CaCO_3$ concentration was measured by monitoring soil CO_2 efflux following HCl addition. Topsoil (0–30 cm) texture, pH and $CaCO_3$ concentration are reported in Table 1.

2.5. Organic C and total N measurements

All topsoil (0–30 cm) samples were ground to 100–200 μm. Some of the samples (mostly soils developed on mudstone, grainstone and chalk) contained inorganic C (carbonates). Decarbonation was achieved using the protocol proposed by Harris et al. (2001). Briefly, 30 mg of ground samples were weighed in 5 ∗ 9 mm silver boats to which 50 μL of distilled water was added. Samples were put in a glass bell jar, next to a beaker containing 100 mL of concentrated HCl (12 mol/L). The vacuum was made in the jar and the samples let in this HCl saturated atmosphere for the acid to penetrate in water and dissolve the carbonates. After 8 h, decarbonated samples were taken out of the jar and dried at 60 °C for at least 48 h. Silver boats were then placed in 10 mm ∗ 10 mm tin boats to be analyzed for C and N.