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Fine resolution map of top- and subsoil carbon sequestration potential in France

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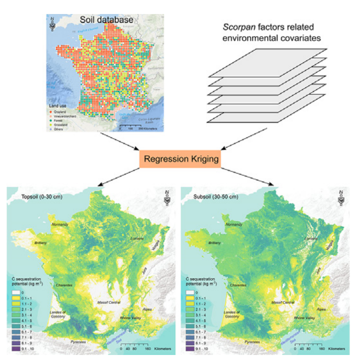
HIGHLIGHTS

- SOC sequestration potential was assessed by unbiased sampling for France.
- Regression kriging was applied for modelling and mapping.
- Controlling factors of SOC sequestration potential differ from topsoil to subsoil.
- Subsoil has a larger SOC sequestration potential.

GRAPHICAL ABSTRACT



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ABSTRACT

Although soils have a high potential to offset CO_2 emissions through its conversion into soil organic carbon (SOC) with long turnover time, it is widely accepted that there is an upper limit of soil stable C storage, which is referred to SOC saturation. In this study we estimate SOC saturation in French topsoil (0–30 cm) and subsoil (30–50 cm), using the Hassink equation and calculate the additional SOC sequestration potential (SOC_{sp}) by the difference between SOC saturation and fine fraction C on an unbiased sampling set of sites covering whole mainland France. We then map with fine resolution the geographical distribution of SOC_{sp} over the French territory using a regression Kriging approach with environmental covariates. Results show that the controlling factors of SOC_{sp} differ from topsoil and subsoil. The main controlling factor of SOCsp in topsoils is land use. Nearly half of forest topsoils are over-saturated with a SOC_{sp} close to 0 (mean and standard error at 0.19 ± 0.12) whereas cropland, vineyard and orchard soils are largely unsaturated with degrees of C saturation deficit at $36.45 \pm 0.68\%$ and $57.10 \pm 1.64\%$, respectively. The determinant of C sequestration potential in subsoils is related to parent material. There is a large additional SOC_{sp} in subsoil for all land uses with degrees of C saturation deficit between $48.52 \pm 4.83\%$ and $68.68 \pm 0.42\%$. Overall the SOCsp for French soils appears to be very large (1008 Mt C for topsoil and 1360 Mt C for subsoil) when compared to previous total SOC stocks estimates of about 3.5 Gt in French topsoil. Our results also show that overall, 176 Mt C exceed C saturation in French topsoil and might thus be very sensitive to land use change.

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1. Introduction

The Paris Climate Agreement reached at the COP21 aims at limiting global warming to 2 °C above pre-industrial levels before the end of the century. To achieve this goal, global annual emissions need to be limited at 9.8 Gt C at 64% probability (Meinshausen et al., 2009). Soil organic carbon (SOC) sequestration can make a significant contribution to offset CO_2 increase in the atmosphere by transferring it into long-lived soil C pools (Lal, 2004; Paustian et al., 2016). Consequently, at the COP21, the initiative "4 per 1000 carbon sequestration in soils for food security and the climate" (4 per 1000, http://4p1000.org/understand) was launched with an expectation to increase global SOC stocks by 0.4% y^{-1} as a compensation for global GHG emissions (Minasny et al., 2017; Soussana et al., 2015). The 4 per 1000 initiative also states that increasing SOC contributes to combat soil degradation, increases food security and enhances agriculture adaptation to climate change (Soussana et al., 2015). In order to achieve the 4 per 1000 target, the annual soil sequestration rate should be 0.6 t C ha^{-1} y^{-1} globally, and could be achieved largely by restoring and improving degraded agricultural lands and changes in crop rotations and agricultural practices (Batjes and Sombroek, 1997; Dignac et al., 2017). This soil sequestration rate cannot be reached everywhere due to the high spatial heterogeneity of SOC stocks and sequestration potential but global studies suggested that 0.2 to 0.5 t C ha^{-1} y^{-1} is feasible at many locations in the world (Paustian et al., 2016; Minasny et al., 2017). Being constrained by agronomic, economic and social challenges (e.g., need for dramatic changes in crop management, tradeoffs with agricultural production), the feasibility of achieving the 4 per 1000 target may be questionable (Paustian et al., 2016; Zomer et al., 2017).

It is generally accepted that there is an upper limit of soil stable C storage, which is referred to as SOC saturation (Hassink, 1997; Six et al., 2002; Stewart et al., 2007). Organic C saturation mainly depends on the intrinsic soil potential to stabilize soil organic matter (SOM) against microbial mineralization, though non-microbial degradation also matters during tillage (Baldock and Skjemstad, 2000; Balesdent et al., 2000). Mechanisms responsible for C stabilization in soils are diverse, variable and still not fully understood. However, the fine mineral fraction is considered to play a major role (Baldock and Skjemstad, 2000; Arrouays et al., 2006) and used as a proxy for soil C stabilization potential (Hassink, 1997). Hassink (1997) proposed an equation to describe the relationship between stable C saturation and the soil fine fraction (<20 μm, clay and fine silt) using a statistical approach based on a wide range of topsoils from temperate and tropical regions. The C saturation deficit or sequestration potential can be calculated as the difference between the theoretical C saturation and the actual SOC stored in the fine fraction. This equation has been used in several studies to calculate sequestration potential at regional or national scales (Angers et al., 2011; Wiesmeier et al., 2014b). Angers et al. (2011) estimated the sequestration potential of agricultural topsoils in France based on 1.5 million legacy soil data from soil tests requested by farmers and then mapped them at the administrative unit level. Wiesmeier et al. (2014b) estimated the sequestration potential of topsoil in southeast Germany and quantified the total sequestration potential stocks based on the bulk density and land area under different land covers. These previous studies used a relatively coarse resolution and did not consider the subsoil. Because of their generally lower SOC content, subsoil horizons are generally believed to offer a large potential for C sequestration (Lorenz and Lal, 2005). However, the C saturation deficit of subsoil horizons has seldom been estimated (Castellano et al., 2017; Reis et al., 2014), and to our knowledge, never mapped. In order to improve land management and identify the locations with high potential to sequester C, it is necessary to develop a better understanding and detailed spatial distribution of SOC sequestration potential at national scale, including the subsoil horizons.

The objectives of this study were three folds:

(1) Determine the SOC sequestration potential for topsoil and subsoil in France;
(2) Build prediction models of SOC sequestration potential for topsoil and subsoil based on relationships with soil-forming environmental covariates;
(3) Produce high resolution maps of SOC sequestration potential for topsoil and subsoil.

2. Materials and methods

2.1. Site specific soil data

The soil data used in this study were obtained from 2092 sites from the first campaign of the French soil monitoring network (RMQS) between 2001 and 2009 (Jolivet et al., 2006), which covers entire metropolitan France (around 550,000 km^2) including different soil, climate, relief and land cover conditions (Fig. 1). The RMQS is based on a 16 km × 16 km square grid and all sites are selected at the center of each grid cell. When sampling the exact location was not possible, a site was selected as close as possible to the grid center (Martin et al., 2010). On basis of an unaligned sampling design with a 20 m × 20 m square, 25 individual core samples were collected from topsoil (0–30 cm) and subsoil (30–50 cm) by a hand auger. These individual core samples were mixed into a composite sample for each soil layers. Then composite samples were air-dried (controlled at a temperature of 30 °C and an air-moisture of 30%) and sieved to 2 mm before laboratory analysis at Soil Analysis Laboratory of INRA in Arras, France. Apart from these composite samples, a soil pit was dug at 5 m from the south border of the 20 m × 20 m square, from which the main soil characteristics were recorded and six bulk density measurements were collected, three within the topsoil layer and three within the subsoil layer (Martin et al., 2009). The topsoil thickness was taken as 30 cm for forest and pasture soils, and deepest tillage depth for arable soils. For some sites, soils were so thin that subsoil did not exist. SOC was determined by dry combustion using a CHN elemental analyzer (Thermofisher NA2000). Particle-size distribution was determined for clay (0–2 μm), fine silt (2–20 μm), coarse silt (20–50 μm), fine sand (50–200 μm) and coarse sand (200–2000 μm) by the pipette method (NRCS, 2004).

2.2. Calculation of C saturation and sequestration potential

The C saturation of particle-size < 20 μm was calculated according to the equation proposed by Hassink (1997):

$$C_{sat} = 4.09 + 0.37 \times finefraction \quad (1)$$

where C_{sat} is the C saturation (g kg^{-1}) and *finefraction* is the content of particle-size < 20 μm (%).

As the C saturation deficit is calculated by the difference between C saturation and the measured C of fine fraction (C_{fine}), an approach for estimating the C_{fine} from the total SOC in our database had to be developed. Based on previously published data (Angers et al., 2011; Balesdent, 1996; Jolivet et al., 2003), the C_{fine} content was assumed to comprise 85% of the total SOC in cultivated topsoil (cropland and vineyard/orchard). To derive more reliable C_{fine} proportions in total SOC for forest, grassland in both topsoil and subsoil, we gathered a few existing data from France, summarized related studies from countries with similar climate to France, and assigned weighted average values for topsoil and subsoil under different land uses (Table 1). Limited by available data sources, the definition of fine fraction varied from 0 to 20 μm to 0–63 μm, but there were no significant differences between them (Balesdent et al., 1998; McNally et al., 2017). In the end, C_{fine} of forest and grassland topsoil was assumed to comprise 66% and 69% of the total SOC while values were 75%, 86% and 93% for forest, grassland and cultivated subsoil respectively. Averaged values from aforementioned land uses were used for other land uses in topsoil (73%) and subsoil (85%).