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Modelling the impact of declining soil organic carbon on soil compaction: Application to a cultivated Eutric Cambisol with massive straw exportation for energy production in Northern France

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ABSTRACT

Loss of organic matter has been recognized as being a major threat to soils in Europe with important consequences for the physical functioning of soils. We present the result of a numerical analysis of the integrated effects of changes in soil porosity and soil water status, along with decreased soil organic carbon (SOC) and the subsequent changes in the risk of compaction. This study concerns the impact of straw exportation on the risk of soil compaction. We evaluated the risk of compaction of a cultivated Eutric Cambisol in Northern France having a dominant silt loam soil texture, by simulating vehicle wheeling during sugar beet cropping for contrasting soil organic carbon contents (4.7, 11.1 and 23.4 g kg^{-1}). To do this, we coupled two models: (1) a crop model (STICS) to calculate the changes in the water content of the 0–30 cm depth layer; and (2) a compaction model (COMPSOIL) to calculate soil stresses as a function of vehicle characteristics. Our study suggests that a decrease in SOC reduces the risk of topsoil deformation due to a decrease in soil water content, which tends to augment soil precompression stress. The method requires improvement in the future because it is very sensitive to input parameters for soil physical properties. Nevertheless it provides the first method for evaluating the impact of SOC decline on soil compaction. Its genericity permits it further applications to various soil management practices that decrease SOC.

1. Introduction

The continued removal of crop residues combined with the use of inorganic fertilizer instead of organic manure and intensive tillage leads to a decline in organic matter over time (Lal, 2009). Recently, increased interest in renewable forms of energy such as biofuels as possible alternatives to fossil fuels intensifies this issue (Wilhelm et al., 2004; Lal, 2005; Monforti et al., 2013). Thus more research is required on the sustainability of agroecosytems subjected to management practices that risk depleting soil organic carbon (SOC), by taking into account the major role played by SOC in maintaining the physical and chemical balance of soil, thus sustaining soil microbial activity and enabling high crop yields (Reeves, 1997).

Different approaches have been proposed in the literature to establish a threshold for SOC with regard to soil physical properties (Loveland and Webb, 2003; Dexter, 2004). These approaches consider the effects of SOC on soil aggregate stability, soil porosity and water retention properties. A decrease in SOC leads to decreased aggregate stability (LeBissonnais, 1996) and increased soil bulk density (Soane, 1990). These changes in soil physical properties have been studied for a long time, and several SOC-based pedotransfer functions (PTF) are now available that could help to estimate the water retention properties and bulk density of soils (Wösten et al., 2001; McBratney et al., 2002). Dexter et al. (2008) proposed relationships for estimating the effect of SOC on both porosity and water retention properties, based on a mechanistic approach describing the interactions between SOC and pores. To date, these approaches have not considered the effects of SOC on the sensitivity of soil to compaction.

Mechanical soil compaction due to the increased traffic and weight of farm machinery on agricultural fields has gained

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increasing attention as it is a serious problem for intensive agriculture (European Commission, 2006). Soil compaction affects major soil physical properties of ecohydrological importance, such as water infiltrability and root penetrability, and thus processes such as vadose zone moisture regimes, plant transpiration, and, finally, plant growth and yield (Soane and van Ouwerkerk, 1994).

Our understanding of soil compaction process is based on the response of a soil to an applied stress. Soil strength and namely the compression behaviour of soil is usually measured at core scale in the laboratory using confined compression tests. Compression curves show the relationship between the stress applied on a soil sample and volumetric parameters such as strain, void ratio and porosity. They express two main mechanical parameters: (i) precompression stress, p_c, beyond which plastic deformation occurs; and (ii) the slope of the virgin compression line, VCL, namely the compression index C_c. Precompression stress is an indicator of a soil's load support capacity; the compression index, represents an indicator of soil compressibility.

The impact of SOC on soil mechanical strength is not straightforward (Soane, 1990; Arthur et al., 2013). Different authors have reported that SOC has a direct effect on soil mechanical strength, but that this effect differs for different types of organic matter (plant residue types, different forms of manure application practices) and for organic matter in different states of decomposition (fresh crop residue, humified organic matter) (Soane, 1990; Zhang et al., 1997; Vidal-Beaudet et al., 2009; Arthur et al., 2013). The effects of SOC on soil mechanical strength depend on soil texture and soil water content. For example, a decrease in SOC increases precompression stress p_c for sandy loam (Lebert and Horn, 1991), whereas SOC decreases it for clay loam when approaching saturation (suction lower than 10 kPa) (Pereira et al., 2006). Moreover, a decrease in SOC is also expected to indirectly affect soil mechanical strength due to changes in two main factors: (i) soil water content at wheeling, and (ii) soil structure before wheeling. Both these factors are expected to govern the soil mechanical strength more drastically than the effect of SOC (Lebert and Horn, 1991; Arthur et al., 2013).

The purpose of this paper is to describe the use of numerical experiments as an alternative to long-term experiments to better comprehend such complex interactions. Our approach combines a crop model with a soil compaction model in view to integrating the various effects of SOC on soil porosity, hydrological and mechanical properties. Analytical compaction models have been widely applied in the agronomic context, as reviewed in Défossez and Richard (2002), and Keller and Lamande (2010). These models have been used to predict the risk of soil compaction as a function of soil, climatic conditions and type of agricultural machines, to provide advice for farmers, and in the framework of legislation on soil protection at larger scales (Horn and Fleige, 2003; van den Akker, 2004; Lozano et al., 2013). These works facilitated the development of more efficient strategies to reduce compaction due to the excessive use of agricultural machinery. The identification of areas at risk of soil compaction is a key task in the area of soil protection policy, but analytical models require data on soil mechanical behaviour that are difficult and expensive to collect. Therefore other methods for assessing this risk have been proposed based on expert systems (Tobias and Tietje, 2007), on classification systems for compaction vulnerability (Spoor et al., 2003; Jones et al., 2003; Zink et al., 2011), on PTFs (Horn and Fleige, 2009) and probabilistic models (Troldborg et al., 2013). These different methods allow examining the impact of climatic conditions, soil characteristics and land management. However, the impact of a decrease in SOC on soil compaction has been given little attention. Since analytical models integrate numerous processes, they can be used to explore interactions between mechanisms and thus provide better understanding of the effect of soil management on soil deformability, in particular the impact of crop residue management. Nonetheless, the need for parsimony required by risk mapping and soil protection policy also demand methods that require few parameters as inputs.

This study serves both these objectives: (i) better comprehension of the effect of decreased SOC on the risk of soil compaction, and (ii) the development of a tool potentially applicable to other contexts for estimating soil compaction risk with few parameters as inputs (e.g. manure application practices in agriculture, biomass exportation in forestry, etc.). We present a tool which combines process-based models and PTF functions developed for applications with sparse information. This tool was used to estimate the number of successive workable days without compaction for three levels of straw exportation. The error induced by estimating soil parameters using PTF is calculated, and we discuss the potential and limitations of this tool.

2. Materials and methods

2.1. Methodology

We consider the overall impact of massive straw export on soil mechanical strength. The range of SOC considered in this study accurately reflects the long-term trend observed in SOC in conventional cropping systems that systematically export straw residue (Lal, 2009). We examine the impact of declining SOC on the risk of compaction by simulating the effect of SOC on soil water conditions and soil porosity at wheeling, both of which have a considerable impact on soil strength. Before describing the method in detail, we give a global view of the approach (Fig. 1). As soil compaction is quite prevalent in plots subjected to continuous cultivation of sugar beet (Boizard et al., 2002), we explored the soil compaction process using sugar beet crops for the case study. The sugar beet crop is a major crop in Northern France that is included in most crop rotations and presents a large risk of compaction due to the heavy weight of harvesting equipment. Our modelling approach couples STICS (Brisson et al., 1998, 2003), which simulates plant growth as a function of soil water content (SWC), with COMPSOIL (O'Sullivan et al., 1999), an analytical model that quantifies soil compaction as a function of SWC. These models require specific parameterizations for certain soil physical properties, namely soil porosity, soil water retention properties and soil mechanical strength. These parameters were described as unique functions of SOC (pedotransfer functions). Further, the risk of soil compaction was quantified by calculating the number of successive days without severe compaction during sowing and harvesting periods for different levels of SOC.

The consequences of massive straw exportation on soil physical behaviour were studied in a loamy soil with different SOCs (Table 1). We investigated this change in soil physical behaviour during a growing season as a function of climatic conditions on the date of field operations and for different agricultural machines used for various field operations (Table 2).

The methodology described in detail in the following consists of three steps, as schematized in Fig. 1:

- determination of the evolution of soil physical parameters listed in Table 3 using SOC-based PTFs and a model of soil porosity (step 1);
- simulation of the daily dynamics of soil water content (SWC) as a function of meteorological conditions in spring and autumn, using the STICS crop model (step 2);
- quantification of the soil compaction risk as a function of SWC, using the COMPSOIL model (step 3).