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Multi-criteria indices to evaluate the effects of repeated organic amendment applications on soil and crop quality

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ABSTRACT

The objective was to develop a multi-criteria tool to compare fertilizing practices either based on mineral fertilizer (CONT + N) or repeated applications of exogenous organic matter (EOM) and considering the positive but also the negative impacts of these practices. Three urban composts (a municipal solid waste or MSW, a co-compost of sewage sludge and green waste (GWS), and biowaste (BIO)) and a farmyard manure (FYM) have been applied biennially over 14 years. Soils and crops were sampled repeatedly and >100 parameters measured. The development of different quality indices (QI) was used to provide a quantitative tool for assessing the overall effects of recycling different types of EOM. A minimum data set was determined and 7 indices of soil and crop quality were calculated using linear scoring functions: soil fertility, soil biodiversity, soil biological activities, soil physical properties, soil contamination ("available" and "total") and crop productivity. All QI varied between 0 and 1, 1 being the best score. EOM amendments significantly increased soil biodiversity, biological activities and physical properties with intensity generally depending on their characteristics. FYM was the most efficient EOM to improve soil biological properties. EOM application lead to similar yields as mineral fertilizers but grain quality was slightly decreased. Thus, mineral fertilizers remained more efficient at improving crop productivity index (QI = 0.88) than EOM although BIO was not significantly different than CONT + N. All EOM improved soil fertility but only BIO was significantly higher (QI = 0.86). EOM added a range of nutrients but an excess of P (e.g. GWS) can negatively impact the soil fertility index. EOM negatively affected the soil contamination index when considering total concentrations but decreased available fractions and consequently the risks of transfer. BIO was the most efficient EOM for most indices including improving the index of "available" soil contamination. This study demonstrated the positive impact of repeated EOM applications on soil and crop quality in a loamy soil.

1. Introduction

Within the framework of developing circular economy and in order to loop the biogeochemical cycles, the recycling of exogenous organic matters (EOM) on cropped soils is being encouraged in Europe (European Commission, 2010). The EOM represent potential sources of nutrients (N, P...) for crops and can partially substitute the use of mineral fertilizers (Chalhoub et al., 2013). Regular applications of EOM to soil can also be a way of restoring soil organic matter content in intensively managed cultivated soils and contributing to carbon (C) storage in soils (Peltre et al., 2012). Manures have been traditionally spread on cropped soils but in the areas where animal breeding is scarce, the recycling of EOM of urban origin may be an alternative opportunity, limiting landfilling or incineration (Houot et al., 2014). In addition to positive effects on soil fertility, EOM applications may improve soil biodiversity and biological activities (Garcı'a-Gil et al., 2000), aggregate stability and soil structure (Annabi et al., 2011; Diacono and Montemurro, 2010) and water infiltration by increasing soil porosity (Haynes and Naidu, 1998). However, negative impacts

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may occur and have also to be taken into account. Indeed EOM may contain contaminants such as pathogens, organic contaminants or trace elements (Belon et al., 2012) that may accumulate in soils and/or be transferred to plants and water. To assess the potential risks associated to the application of EOM to soils, considering total concentrations of contaminants is not sufficient (Burakov et al., 2010), and available and mobile fractions must also be taken into account (Harmsen et al., 2005). Additional negative impacts like a decrease of pH, or an excessive input of nutrients due to *e.g.* simultaneous N and P addition while EOM application should also be considered. The intensity and duration of positive and negative effects of EOM amendments on soil depend on the characteristics of these EOM, the applied doses, the frequency of applications and the cropping system.

Soil quality defined as "the capacity of soil to perform its functions" (Lal, 1994) can be evaluated for different purposes (Karlen et al., 2003): (1) the suitability for different land uses (e.g. crop production, housing) or (2) the assessment of management practices for a specific use, the assessment of farming practices on cropped soils in our case.

In most cases, a combination of physical, biological and chemical parameters is used to develop robust interpretation of soil quality (Andrews et al., 2004). "Inherent" soil parameters such as texture, mineralogy or depth are determined by *e.g.* parent material, climate or topography and are use-invariant. They are used to qualify soil for different land-uses (Seybold et al., 1999). For example, "inherent" parameters have been used to compare soil fertility, define the best soils for crop production or soil capacity at receiving liquid sludge or waste water reuse (Robinson et al., 2009). On the other hand, soil "dynamic" parameters such as organic matter content, nutrient availability, biological activities and community structure or total and available trace element concentrations may be impacted by anthropic activities. Such parameters are of interest to assess the effects of management practices (soil tillage, organic farming or EOM recycling) on soil and crop qualities. Time scales differentiate both types of parameters: soil "inherent" parameters need very long periods to develop and they may be considered as constant at a human scale, whereas soil "dynamic" parameters might be altered rather rapidly through human interventions (Robinson et al., 2009). Moreover, the evaluation of dynamic parameters focuses on the topsoil, where most likely they have been altered by human interventions.

A selection of relevant indicators is always needed to assess soil quality. Parameters are defined as all data available, whereas indicators are defined as the most sensitive or relevant parameters as proxy of a soil property or modified by the practice, not expensive, accessible to many users and easy to measure and interpret, meaning that references are available (Doran and Parkin, 1996; Rutgers et al., 2012). A minimum data set (MDS) of indicators has to be chosen to assess the impact of a practice on soil quality. Currently, there is no consensus on this MDS for soil functioning (Morvan et al., 2008). No universal list of indicators suitable for all regions and ecosystem functions exists (Seybold et al., 1998). When the potential indicators are too numerous, a method has to be defined to select the most relevant ones before aggregating them into a unique soil quality index or developing a multi-criteria tool considering several specific indices. The choice of MDS may be based on (a) expert opinion (Doran and Parkin, 1996; Karlen and Stott, 1994; Larson and Pierce, 1991) or (b) statistical method (Andrews et al., 2004; Shukla et al., 2006). Mukherjee and Lal (2014) compared the two approaches and showed that they were correlated (r = 0.97).

In the present work, the objective was to develop a multi-criteria tool to compare fertilizing practices either based on mineral fertilizers or repeated applications of EOM and considering the positive but also the negative impacts of these practices. The development of different quality indices was used to provide a quantitative tool for assessing the overall effects of recycling different types of EOM. The originality consisted in distinguishing 6 different soil quality indices: soil fertility, soil biodiversity, soil biological activities, soil physical properties, two soil contamination states (considering total and available concentrations of contaminants) and one index of crop quality, while most previous studies developed a unique and global index. The choice of indicators and their aggregation were based on a statistical approach. Indices were developed from an experimental site set up in 1998 and after 7 applications of EOM.

2. Materials and methods

2.1. Field site and sampling

The long-term field experiment QualiAgro (INRA-Veolia Recherche & Innovation partnership, Feucherolles, France) has been started in 1998 (Houot et al., 2002). The soil is a luvisol with the following initial characteristics in the plough layer (0–28 cm): clay, 150 g kg^{-1}; silt, 790 g kg^{-1}; sand, 60 g kg^{-1}; organic carbon, 11.0 g kg^{-1}; organic nitrogen, 1.0 g kg^{-1}; pH, 6.9. A farmyard manure (FYM) and 3 urban composts, including a municipal solid waste compost (MSW issued from the composting of the residual fraction of the municipal solid waste after separate collection of packaging, paper, glass, cans . . .), a biowaste compost (BIO issued from the co-composting of green waste and home sorted and separately collected of the fermentable fraction of the municipal solid waste), a co-compost of sewage sludge and green waste (GWS) have been applied every other year in September, at doses equivalent to $\sim$ 4 tC ha^{-1} (18–35 t fresh matter ha^{-1}) corresponding to 1.5–2-times the doses that are typically applied by farmers. EOM were added on wheat stubbles of a maize-wheat succession (barley in 2007 due to a regional attack of *Diabrotica virgifera* on maize). After 7 applications, the inputs of contaminants (trace elements, pathogens or organic contaminants) in soil remained below the regulatory limits. The design of the field experiment includes four blocks of replication of the different treatments including amended and control plots (450 m^2 each). The control treatment (CONT + N) receives mineral nitrogen (25% nitrate, 25% ammonium and 50% urea) in doses calculated to comply the crop needs. More information about the composting process and the field experiment can be found in Annabi et al. (2007, 2011). In each plot, before each EOM application, ten soil cores are sampled in the ploughed horizon (0–28 cm) and pooled for monitoring physico-chemical characteristics. All EOMs are also sampled during their application for analysis. Each year, crop yields are determined and grains sampled for further analyses. In the present study, the most recent samplings of soil (September 2011 for physico-chemical parameters) and crop (wheat 2011) were considered. Additional soil samplings occurred in the ploughed horizon for other characterizations: May 2005 for aggregate stability, April 2013 for other physical parameters; March 2009 and September 2011 for biological parameters; September 2011, April 2012, March 2013 and October 2013 for enzymatic activities; March 2009 for the *oprF gene* as a pathogen marker and September 2011 for others pathogens and antibiotic resistant genes (**Table S1**).

2.2. Analyses

All methods used to analyze soils and crops are listed in **Table S1** and in **Table S2** for EOM. They are summarized below.

Different analyses were performed to characterize EOM: pH, organic C, total N, P, mineral N $CaCO_3$, total concentrations of Ca, Cr, Cu, Mg, Ni, K, Zn, Pb and Cd. The index of residual organic carbon (I_{ROC}) that represents the proportion of organic matter potentially