Predicting soil organic matter stability in agricultural fields through carbon and nitrogen stable isotopes

Tim De Clercq [a], [*], Maria Heiling [b], Gerd Dercon [b], Christian Resch [b], Martina Aigner [b], Leo Mayer [b], Yanling Mao [c], Annemie Elsen [d], Peter Steier [e], Jens Leifeld [f], Roel Merckx [a]

[a] Division of Soil and Water Management, Department of Earth and Environmental Sciences, KU Leuven, Kasteelpark Arenberg 20, 3001 Heverlee, Belgium
[b] Soil and Water Management & Crop Nutrition Laboratory, Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, Department of Nuclear Sciences and Applications, International Atomic Energy Agency, Vienna, Austria
[c] Department of Resources and Environmental Sciences, Fujian Agriculture and Forestry University, Fujian, China
[d] Soil Service of Belgium, Willem de Croylaan 48, BE-3001 Leuven, Belgium
[e] Isotope Research and Nuclear Physics, VERA Laboratory, University of Vienna, Vienna, Austria
[f] Climate/Air Pollution Group, Agroscope, Institute for Sustainability Sciences ISS, Zürich, Switzerland

ARTICLE INFO

ABSTRACT

In order to evaluate the sustainability and efficiency of soil carbon sequestration measures and the impact of different management and environmental factors, information on soil organic matter (SOM) stability and mean residence time (MRT) is required. However, this information on SOM stability and MRT is expensive to determine via radiocarbon dating, precluding a wide spread use of stability measurements in soil science. In this paper, we test an alternative method, first developed by Conen et al. (2008) for undisturbed Alpine grassland systems, using C and N stable isotope ratios in more frequently disturbed agricultural soils. Since only information on carbon and nitrogen concentrations and their stable isotope ratios is required, it is possible to estimate the SOM stability at greatly reduced costs compared to radiocarbon dating. Using four different experimental sites located in various climates and soil types, this research proved the effectiveness of using the C/N ratio and $\delta^{15}N$ signature to determine the stability of mOM (mineral associated organic matter) relative to POM (particulate organic matter) in an intensively managed agro-ecological setting. Combining this approach with $\delta^{13}C$ measurements allowed discriminating between different management (grassland vs cropland) and land use (till vs no till) systems. With increasing depth the stability of mOM relative to POM increases, but less so under tillage compared to no-till practises. Applying this approach to investigate SOM stability in different soil aggregate fractions, it corroborates the aggregate hierarchy theory as proposed by Six et al. (2004) and Segoli et al. (2013). The organic matter in the occluded micro-aggregate and silt & clay fractions is less degraded than the SOM in the free micro-aggregate and silt & clay fractions. The stable isotope approach can be particularly useful for soils with a history of burning and thus containing old charcoal particles, preventing the use of ^{14}C to determine the SOM stability.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Soils play a major role in the global carbon (C) cycle. The terrestrial soil organic carbon (SOC) pool contains about two and a half times more organic C than the vegetation and about twice as much C as is present in the atmosphere (Batjes, 1998). Down to a depth of 1 m the soil is estimated to contain 1500 Pg C (Batjes, 1996). Despite their low C concentrations, subsoil horizons are estimated to contain half of this C pool (Schmidt et al., 2011). Over the last 150 years cultivation and disturbance of agricultural soils have caused a net loss of between 40 and 90 Pg C globally (Lal and Bruce, 1999; Lal, 2004). These losses can be replenished by restoring degraded soils, converting marginal agricultural soils to restorative land use and adopting recommended management practices (Lal, 2004). Replenishing these C stocks has multiple benefits, for example increasing soil health and sequestering atmospheric CO_2. Considering agricultural land alone, approximately 5.5–6.0 Gt CO_2 eq. could potentially be stored each year, which

amounts to approximately one sixth of global annual CO_2 emissions (Smith et al., 2008; Olivier et al., 2012).

However, in order to evaluate the sustainability and efficiency of soil carbon sequestration measures and the impact of different management and environmental factors, information on soil organic matter (SOM) stability and mean residence time (MRT) is required. Since SOM stabilization is a combination of short- and long-term processes, any disturbance of these processes may result in the decomposition of young and old SOM alike (Schmidt et al., 2011; Lal et al., 2012). Agricultural soils can thus turn from a carbon sink into a carbon source very rapidly. A clear example is the conversion of tropical peat soils into agricultural land causing a massive CO_2 release due to profile drainage and subsequent oxidation of the stabilized SOM (Hooijer et al., 2010). In various parts of Western Europe knowledge of SOM stability is also needed for a different reason. SOM decomposition entails a release of mineral nitrogen and excess nitrogen can leach to surface- and groundwater causing eutrophication. While historically, nitrogen release from SOM has been mastered adequately by empirical models, the more recent trends in (i) higher amendments of organic sources of nutrients like composts and (ii) changes in soil tillage techniques seem to have changed the distribution of SOM among fractions of different stability, possibly leading to a changed nitrogen release.

Radiocarbon dating is one of the only tools useable to study SOM dynamics on decadal to millennial timescales. The SOM ^{14}C content provides information on the time since C was fixed from the atmosphere and as such on SOM stability and MRT (Trumbore, 2009). However, this method is expensive, precluding a wide spread use of stability measurements in soil science. Conen et al. (2008) developed an alternative model to estimate the SOM stability of an Alpine, permanent grassland at steady state conditions. This model is based on the isotopic fractionation of the heavy stable isotope of nitrogen (^{15}N) during decomposition, which goes hand in hand with a decreasing C:N ratio during organic matter degradation. Due to the decreasing C:N ratio during litter decomposition and SOM formation as described in Fig. 1, excess mineral N is released by soil micro-organisms. Isotopic fractionation during this nitrogen

dissimilation and export process results in the preferential loss of the lighter ^{14}N from the SOM, leading to a highly ^{15}N enriched and stable SOM fraction (Dijkstra et al., 2008; Coyle et al., 2009). Since only information on carbon and nitrogen concentrations and their stable isotope ratios is required, it is possible to estimate the SOM stability at greatly reduced costs compared to radiocarbon dating. To date this model has only been tested under non-agricultural, undisturbed conditions. In this paper the validity of the above concepts will be tested in more frequently disturbed agricultural soils.

Alternatively — in specific cases like C_3/C_4 vegetation changes — the ^{13}C content of SOM can be used to gain information on stability and MRT. A shift in cover crops from C_3 to C_4 plants changes the $\delta^{13}C$ signal of the inputs, which can then be traced in the SOM to calculate the MRT (Balesdent and Mariotti, 1987; Balesdent and Balabane, 1992; Collins et al., 1999). Unfortunately this C_3–C_4 shift is not always present at the site of interest. However, the ^{13}C content of organic matter also increases upon microbial degradation, without cropping changes and is most visible with increasing depth (Rumpel and Kögel-Knabner, 2011). As both C and N isotope ratios are influenced by microbial degradation, integrating the $\delta^{13}C$ signature into the model could increase the accuracy of the SOC stability estimation. To our knowledge no attempt has been made yet to combine carbon and nitrogen stable isotope ratios as a proxy for SOM stability.

Moreover the simple two pool model used by Conen et al. (2008) only yields limited information on the nature of the stabilization mechanisms involved. While SOM stability and protection are governed by the interaction of biochemical recalcitrance, adhesion to soil mineral particles and physical protection from degradation through particle aggregation, no general consensus exists on fractionation methods for estimating SOM stability (Six et al., 2002b; Jandl et al., 2013). Thus, in order to obtain a more detailed picture of the protection mechanisms involved in SOM stabilization five SOM pools with varying degrees of physical and (bio)chemical protection were isolated based on the fractionation scheme developed by Six et al. (2002a). The principles for determining SOM stability outlined above were applied to these fractions to gain better understanding of SOM stability and its link with aggregate formation.

To summarize, this study has three main goals. We will test the hypothesis that the C:N ratio and $\delta^{15}N$ signature can be used as a proxy for SOM stability in a disturbed agricultural setting. To achieve this the procedure and model described by Conen et al. (2008) will be followed. Secondly, it is tested if the $\delta^{13}C$ depth profile of the study sites can enhance the performance of the model and provide additional information on the degree of SOM stabilization. Thirdly, the application of the C:N ratio and ^{15}N isotope model is linked to a more elaborate soil fractionation scheme based on Six et al. (2002). This will yield a better understanding of SOM dynamics and soil aggregate formation under different management practices. These hypotheses were tested on four long-term field experiments, established on soils poor and rich in soil organic matter in Austria and Belgium.

2. Materials and methods

2.1. Site description

Soil samples were taken from four long term agricultural fields on two locations in Austria and two in Belgium. The sites were selected for their diverse management, climatic and soil characteristics and because a detailed cultivation history was available. The climatic and soil characteristics of these four experimental sites can be found in Table 1.
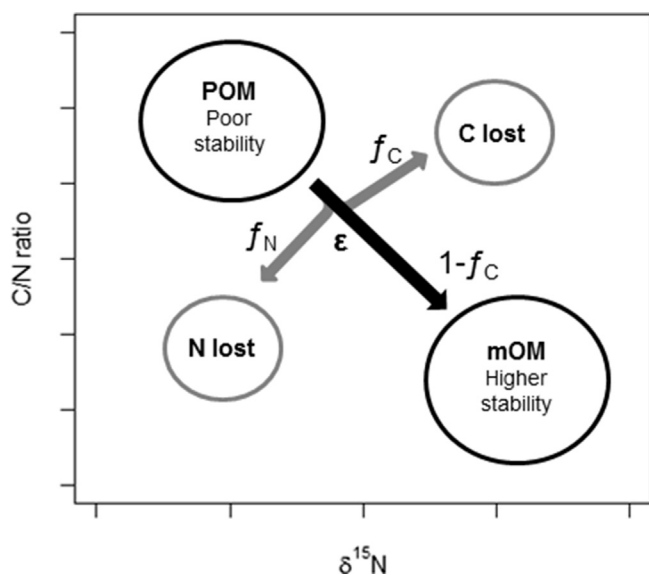

Fig. 1. Theoretical evolution of C/N ratio and $\delta^{15}N$ signature for the particulate organic matter (POM) and mineral-associated organic matter (mOM) fraction as described by the model. f_N: fraction of N lost, f_C: fraction of C lost, ε: fractionation coefficient (Conen et al., 2008).