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Data Collecting Issues and Measuring

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1. Introduction

It has been widely recognized the crucial role of soil monitoring in assessing the effectiveness of the soil measures and agro-environment schemes passed by Regional and local administration in complying the EU's Common Agricultural Policy to soil protection.

There are several problems related to soil OMC measuring and data collection: i) the soil functions that one wants to monitor as well as ii) the methods and procedures of monitoring, also in dependence of iii) the reference scale of monitoring

2. Soil Organic matters and soil functions

Soil functionality depends on amount, quality, and persistence of OM. Soil organic matter is subjected to microbial degradation and its residence time can vary depending on i) chemical recalcitrance, ii) physical protection and iii) soil biological functioning. Recent analytical and experimental advances have demonstrated that molecular structure has only a secondary role in controlling SOM stability, which instead mainly depends on its biotic and abiotic environment (Schmidt et al., 2011, *Nature* 478, 49–56). Using compound-specific isotopic analysis, molecules predicted to persist in soils (such as lignins or plant lipids) have been shown to turn over more rapidly than potentially labile compounds (Marschner et al., 2008; Amelung et al., 2008; Grandy, A. S. & Neff, J. C. *Molecular C dynamics downstream: The biochemical decomposition sequence and its impact on soil organic matter structure and function. Science of the Total Environment* 404, 297-307 (2008). In fact, there is no general consensus about the humification process as relevant for recalcitrance and residence time (Marschner, B. et al. *How relevant is recalcitrance for the stabilization of organic matter in soils? Journal of Plant Nutrition and Soil Science* 171, 91-110 (2008). Kleber, M. & Johnson, M. G. *Advances in understanding the molecular structure of soil organic matter: Implications for interactions in the environment. Advances in Agronomy*, 77-142, 2010) and, rather than verifying the existence of these large, complex molecules, we now understand that these components represent only a small fraction of total organic matter, whereas *in situ* observations find



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smaller, simpler molecular structures (Kleber, M. & Johnson, M. G. *Advances in understanding the molecular structure of soil organic matter: Implications for interactions in the environment. Advances in Agronomy*, 77-142 (2010); von Lützow, M. et al. *Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions - a review. European Journal of Soil Science* 57, 426-445 (2006); Lehmann, J. et al. *Spatial complexity of soil organic matter forms at nanometre scales. Nature Geoscience* 1, 238-242 (2008). Sutton, R. & Sposito, G. *Molecular Structure in Soil Humic Substances: The New View. Environmental Science & Technology* 39, 9009-9015; 2005).

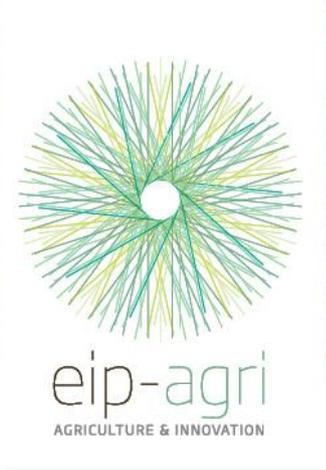
This discrepancy between chemical recalcitrance and residence time can be explained through physical protection mechanisms and physical disconnection between soil organic matter and microorganisms. Physical protection mechanisms can occur at particle-size and aggregate-size level through OC sorption on clay particles, as well as inclusion into micro-aggregates. The soil volume occupied by microorganisms is less than 1%, distributed heterogeneously in small-scale habitats (Ekschmitt, K. et al. *Soil-carbon preservation through habitat constraints and biological limitations on decomposer activity. Journal of Plant Nutrition and Soil Science* 171, 27-35 (2008). Thus physically inaccessible substrates, because of protection by micro-aggregates, sorption on clay surfaces, or disconnection, can persist in the soil even if easily decomposable.

When studying SOM dynamics and soil storage potential, research needs to consider the protection mechanisms affecting SOM persistence and accumulation into the soil. In this view, some questions are relevant for SOM monitoring, as detailed below.

How to assess the persistence of organic matter in the soil?

To monitor SOM potential stability and to separate pools of different residence time several approaches are possible: (1) physical separation of SOM into aggregate, particle size, and density fractions, (2) various wet chemical procedures that fractionate SOM according to solubility, hydrolyzability, and resistance to oxidation or by destruction of the mineral phase and (3) turnover rates estimation through decomposition studies, natural labeling of SOM using stable ^{13}C tracers, *in situ* labeling of SOM with 'bomb' ^{14}C and the ^{14}C -dating technique.

However, these methods can be of limited applicability due to elevated costs (such as labeling), most procedures are not specific enough with regard to stabilization mechanisms, and most available fractionation methods do not yield homogeneous or functional OM pools (von Lützow et al., 2007). No procedure appears capable of distinguishing SOM fractions based on all possible agents for SOM stabilization, which vary in significance among soils and among compounds. Especially the conceptual



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passive pool, which is stabilized by various mechanisms, is still difficult to characterize. All efforts to isolate this pool so far have yielded SOM fractions that are still heterogeneous in terms of turnover times and reveal no causal relationships to stabilization mechanisms.

New emerging methods seem promising in studying the continuum of SOM in the soil matrix: among them thermal analysis techniques permits to assess the stability of SOM against thermal oxidation in controlled conditions and to estimate the size of different pools, as reviewed by Plante et al. (2009). Relationships between SOM thermal stability and soil biological activity were also showed (Grisi et al. 1998; Leifeld and von Lutzow 2014). More direct information on availability of organic substrates to biological decomposition in soil are furnished by calorimetric techniques, which permits the direct measurement of microbial metabolic heat and CO₂ rates associated with SOM biodegradation (Barros et al. 2010; Barros et al. 2011). Moreover, combining microscopy and chemical analysis of soil thin sections can give information on the relationships between microscale distribution of soil organic matter features and their stability (Falsone et al., 2014).

Combination of physical, chemical and incubation SOM fractionation techniques should be used as a tool to better understand stabilization mechanisms and the potential for SOM accumulation in different soils, considering the whole soil profile and its pedogenesis.

How much of the organic matter added to the soil through organic fertilization or composting persist for long time?

Most of amendments added to the soil to improve SOM content are composed by labile materials, poorly humified and potentially subjected to a fast degradation. To improve the stabilization of added organic matter and maintain it in the longer term, more research is needed, considering physical protection mechanisms. Techniques of amendments spreading and incorporation should be well defined also as a function of soil and crop type. Monitoring of new OM incorporation and stabilization should be carried out with the aim to identify the best practices that allow a long term persistence of OM into the soil.

How management influence the persistence of soil organic matter into the soil?

Large efforts have been made in the past decades to assess the impact of agricultural practices on SOM accumulation and stability. The impact of tillage practices, organic management, fertilization, rotation etc. has been studied in most ecosystems. However, in particular in the Mediterranean area, few



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long-term experimental sites are available for these studies. There is the need to identify long-term processes affecting SOM accumulation under different agricultural management, putting more efforts for research in long-term sites.

3. Influence of global warming on SOM decomposition

Decomposition is carried out by microorganisms through enzymatic attack of SOM and microbial respiration: extracellular enzymes degrade soil OM through hydrolytic or oxidative processes, producing assimilable dissolved OM that is rapidly incorporated by microbes. It is known that when substrate availability and enzyme activity do not constrain reaction rates, decomposition rates increase with temperature and this increase can be expressed by the Q_{10} (the rate of change of a biological system as a consequence of increasing the temperature by 10 °C). However, environmental conditions (i.e. moisture, initial temperature), substrate availability and accessibility, metabolic activity, immobilization of enzymes on clay surfaces, microbial communities structure, may affect the temperature sensitivity of SOM decomposition (*Bradford et al. 2008; Malcolm et al. 2008*). Enzymes binding humic substances are more stable to some environmental stresses than free enzymes and can persist longer than microbial cells that produced them. Humic-bound enzymes represent a sink of biochemical energy and slow-release nutrients capable to sustain the ecosystem functionality even in stressed situations; they are considered the last barrier against irreversible soil desertification and are co-responsible of soil resilience. The relationship between decomposability and response of the decomposition rate to temperature, the fate of soil carbon and the feedbacks between soil organic carbon and climate remain unresolved and have been addressed differently in leading climate-carbon models (*Huntingford et al., 2009*). Therefore, accounting for the response of microbial communities to environmental parameters may be needed to adequately predict feedbacks between global change and the decomposition of soil organic C (*Friedlingstein et al. 2006; Thornton et al. 2009*).

How microbial and enzymatic response affect the temperature dependence of SOM decomposition?

Conant et al. (2011) identified three component processes for which variation in rates could affect response to temperature: depolymerization of biochemically complex compounds; production and conformation of microbial enzyme production; and processes that limit the availability of soil OM (adsorption/desorption and aggregate turnover). Immobilized and free enzymes have different sensitivity



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to temperature increase. Also, temperature affects both production and turnover of extracellular enzymes in soils (since turnover is partially due to protease activity), thus possibly indirectly affecting the relationship between decomposability and temperature sensitivity (*Conant et al., 2011*).

Thus, research on how substrate supply regulation (adsorption/desorption and aggregate turnover), microbial efficiency and microbial enzyme production and activity respond to temperature is needed to understand controls over substrates decomposition.

Does stable and labile fractions of organic matter respond in the same way to temperature increase?

How different pools of organic matter respond to temperature increase is not completely understood: i.e. *Benbi et al. (2014)* reported labile and particulate organic matter resulted to be more sensitive than recalcitrant pool, but *Fang et al. (2005)* reported resistant and labile organic matter respond similarly to global warming. Further studies are needed to understand how organic matter different in quality and accessibility respond to the temperature increase, combining laboratory incubation and physical fractionation procedures.

4. Short term indicators of soil organic matter changes

Short-term SOM changes are usually not detectable due to the high background of soil C level. Thus, looking at sensitive early indicators might be considered as a useful tool for SOM accumulation predictions. Indicators should be: (a) sensitive to the presence of the greatest possible number of degrading agents; (b) consistent in the direction of the change undergone in response to a given contaminant; and (c) able to reflect the different levels of degradation. Biochemical soil properties that reflect either the activity of microbial processes or that of hydrolytic soil enzymes are generally used to assess soil quality and health. However, some issues still remain: indicators show a high degree of variability in response to climate, season, geographical location and pedogenetic factors, resulting in contradictory conclusions in different studies (*Gil-Sotres et al., 2005*). Also, the lack of standard analysis methods laboratories, as well as of reference values or broad databases, is a fundamental problem when interpreting the values of biochemical properties, making it difficult to compare data obtained from different laboratories. Finally, a selection of indicators specific to detect changes of SOM is required.



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Is OC (OM) content, as it, a parameter accurate enough to compare different soils?

The topsoil OC (OM) content is the main and simplest indicator to classify and to communicate quickly the situation concerning a single type of soil, a farm or a region (Zdruli et al., 2004).

However the OC (OM) content, as it, give a very poor information, considering how the specific conditions and particularly soil texture, can affect definition of SOC content classes and, above all, their agronomic interpretation. This consideration has the highest relevance in Mediterranean regions, where SOM content is generally low and the topsoil texture shows great variability. Consequently to give a higher significance to a simple, but very widespread indicator like OC (OM) content, it should be highly recommended to relate it to soil texture classes, as shown in tab. 1.

Table 1: Soil Organic Matter content classes for soils of Italy (source: Ministry of agriculture: Guidelines for crops' Integrated Production).

SOM CONTENT (%)			
CLASS	Sandy soils* (sand - loamy sand – sandy loam)	Loamy soils* (loam, sandy clay loam, clay loam, silt loam, silty clay loam)	Clayey soils* (other texture classes)
very low	<0.8	<1.0	<1.2
low	0.8-1.4	1.0-1.8	1.2-2.2
medium	1.5-2.0	1.9-2.5	2.3-3.0
high	>2.0	>2.5	>3.0

*Soil texture classes after USDA classification

Identification of the more reliable short term indicators for organic matter changes

Biologically-active forms of SOM can function as short-term indicators of longer-term changes in SOM. Most used indicators include microbial biomass C, microbial respiration, enzyme activities and related indices (microbial biomass C to total organic C ratio, respiration to microbial biomass ratio, enzyme activity to microbial biomass or to total C ratio). Among enzymes, β -glucosidase indicates the SOM



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decomposition potential and has been proposed as a sensitive indicator of short-term soil TOC changes and of management effects on agricultural soils, since it integrates information on microbial status and soil physico-chemical conditions (*Aon and Colaneri, 2001*).

These biochemical parameters can be used to predict SOM changes in the short term, but there is a need to: i) standardize the methods, ii) identify threshold values, iii) identify and use site-specific factors for the study area (pedoclimatic parameters, vegetation type....), iv) consider seasonal changes, v) define the scale of application.

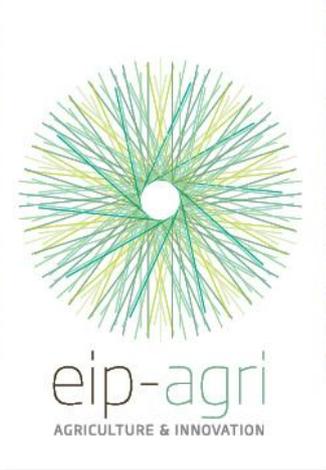
More sensitive and informative complex indices may be elaborated?

Efforts in the use of biochemical properties as indicators of SOM changes should be focused on the search for complex expressions in which several biochemical properties are involved, which are capable of describing soil complexity. There is the need to select a minimum set of indicators that can address the maximum capacity of soil to a specific function. Multidisciplinary approach is essential and complex indices should include biological, chemical and physical indicators.

In this view, a wider use of new rapid and accurate techniques to determine SOM content in the field is desirable in the future.

5. Methods and procedures of monitoring

The costs of soil monitoring are substantial and the reliability of the results often questionable. A reason is that the monitoring activity commonly consists of a network of sampling points which are then spatialized through different inference models. This methodology does not often enable a reliable estimation at the field scale, that is the scale where the agro-environment measures are foreseen and financed. The organic carbon content of the ploughed layer is an important soil feature, which regulates many soil functions. It is therefore considered in Organic Farming (OF) and contemplated in many agro-environment schemes. The adoption of OF is expected to improve soil organic carbon content of the fields as a whole. Nevertheless, the improvement might show local variations, because of the interaction between crop management and other factors, for instance, soil erosion. Using combined soil proximal sensors, like gamma radiation, electromagnetic conductivity, and Vis-NIR spectroscopy, together with satellite or airborne remote sensing can be a way able to reduce the costs of monitoring and increase its reliability.



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Additions below by Dimos P. Anastasiou:

Soil sampling, georeferencing and spectroscopy

Soil surveys at the regional, national or European level are one of the basic tools for soil data collection, and the starting point for any mapping effort, and interpolation of the soil properties from the point measurement scale, to the local level. The use of proximal sensors, as mentioned above, in combination with the reference soil sampling aids to a cost efficient, and faster, non-destructive sampling approach.

Georeferencing of soil surveys is another very important task, since the accuracy of ground measurements influences further processing and analysis for mapping. Accurate and cost efficient georeferencing made with positioning systems today helps surveys be materialized faster, reducing the time of both field and laboratory work for accurate registration of data.

Also, with non-destructive sampling, data collection in situ is faster, and can be applied homogeneously under a common sampling protocol, either at the national or European level. Technological equipment combining accurate and cost efficient georeferencing with such in situ non-destructive measurements at the same time, further aids to the accuracy of soil survey in general, or an SOM/SOC assessment in particular.

Additionally, the spatial co-registration of all the collected data can be easily incorporated into scientific tools, and collected in a central database for further analysis.

At the European and also at the global level, soil spectra libraries using field or laboratory spectroscopic equipment have been developed, usually utilizing the Vis-NIR range of 0.3 to 2.5 micrometers. At the national level, there are various research, local or regional efforts to achieve soil attribute sampling and at the visual and near infrared range also.

Combination of in situ measurements with satellite instrument data

Measurements and monitoring of SOC and SOM at field scale combined with VIS-NIR in situ spectroscopic measurements and remote or airborne sensors can aid towards the improvement of local knowledge and assessment of soil conditions. Issues such as the diffused nature of soil spectra, atmospheric and topographic correction and spectral signature mixtures with the various vegetation types covering the rural landscape can influence significantly the estimation success.



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Terrestrial ecosystem dry biomass, debris and soil organic matter have similar reflectance properties at the visible and infrared parts of the spectrum under wide wavelength sensors, and their spectral distribution is all over the VIS-NIR space, making discrimination even more complex. For example, dry biomass spectra, or soil organic matter spectra, plant cellulose spectra (one of the characteristic components of plant dry biomass) or soil spectra can be highly confused under broadband wavelengths. However, these variables can be better discriminated under denser wavelength observations, such as from a field spectroradiometer monitoring at equidistant intervals of a few or even per one nanometer resolution of the VIS-NIR range.

Airborne or satellite imagery atmospheric corrections to surface albedo is another common challenge for the assessment of various soil properties at a large scale, with incorporation of field survey spectra. Having appropriate atmospheric correction at the temporal and spatial resolution required for combination of field surveys with airborne or satellite imagery can be a valuable tool for soil property assessment at a larger scale, for example for local or regional soil surveys.

Spatial diversity and the complexity of spatial and temporal land cover and land use, and also land use history, which especially in mountainous and less developed areas of the Mediterranean can have large variations, can influence SOM Content and SOC spatial variability. Relatively small farm level size and spatial inhomogeneity of landscape can also be another factor that influences the degree of difficulty using VIS-NIR sensed imagery.

Spatial variability of SOM and SOC can present significant fluctuations within small field distances, and present high variability within an agricultural field. Therefore, while for other environmental variables a medium to high resolution airborne or satellite sensor would be adequate, for the variables of interest a higher resolution could be needed.

Disaggregation of monitored raw spatial data is also one approach followed in order to cover such gaps in depicting local variability of environmental variables. Diffusion of data sources by various sensors monitored at different spatial and temporal scales are also employed and then checked for validity with measured in situ surveys.

Temporal changes of terrestrial ecosystems can also influence the use of spectroscopy in SOM and SOC estimation. Varying degrees of soil humidity and temperature, for example during a natural fluctuation between the wet and dry periods of the year, are directly related to the reflectance of soil spectra. Under



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these varying atmospheric and soil surface conditions reflectance of soil spectra will vary annually, and will also vary in comparison with the reference laboratory measured signals.

SOM can have temporal changes at higher intervals than other soil properties (such as soil structure) depending on agricultural regime, plant species, and various other anthropogenic or natural factors. For example, a drought period can cause reduced biomass accumulation rates, and thus add to the complexity of estimating or predicting SOM.

Combination of spatial statistics and spatial models can incorporate soil surveys, terrain and climatic data and information, land cover and land use factors to a model which inference is made on SOM or SOC incorporating all available data and information, including spectral data. Such modelling approaches can use both the advantages of the VIS-NIR spectroscopy and use other proxy variables to estimate or predict interesting soil properties where field surveys are unavailable. Various krigging methods have been developed and specialised tools are applied in the framework of mapping soil attributes.

Traditional analytical methodologies and existing databases

A large body of soil analysis data are currently available in different laboratories of soil science and governmental or regional agencies. These information often cover a time span of several decades but unfortunately the more ancient data often are not organized according to a geo-reference base, thus the compilation of temporal trends of SOM or SOC content is not reliable outright. Moreover, the different analytical methods adopted prevent in most cases a direct comparison. Although methods for determining soil carbon content are well established from long time, some critical points still remain which need to find a consensus among soil scientists, technicians and farmers before either undertake new campaigns of SOM monitoring or evaluate the effectiveness of soil management and agricultural practices to prevent SOM depletion. In particular, a scientific debate recently restarted about the use of the conventional SOC to SOM conversion factor (van Belemmen factor SOC/SOM 1.724) which was reviewed and criticized by Pribyl (2010) since any empirical factor demonstrated to depend on vegetation cover, OM composition, depth in profile, etc. Thus it was recommended to directly determine soil C content and to not convert it into a SOM value. Source of variations is also the specific analytical method used: among the wet acid digestion procedure, the Walkley-Black method is known to under-estimate the oxidable carbon for incomplete digestion of organic material (Nelson and Sommers, 1996), thus requiring a correction factor which introduces a further uncertainty. Another method commonly used in the past because easy e low expensive is the loss-on-ignition (LOI): it furnishes an estimate of SOM based on weight loss upon



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ignition, but results depend on the temperature of ignition chosen and are affected by overestimation due to soil clay content (Prybil, 2010). Actually the direct determination of C by dry combustion method is the more recommended method (Nelson and Sommers, 1996). All these criticisms suggest that a recognition of existing soil data base should include clear indication of the specific analytical method adopted for SOC determination before exploiting and using such data for modelling soil C trends. Different criticisms there arise also when values of SOC (expressed on a mass basis of a soil sample aliquot) are used to estimate C stock in soil: in this case information on soil bulk density is fundamental in order to convert C data from mass to volume basis, as well information on spatial variability in order to achieve reliable modelling of C distribution on space and on depth.

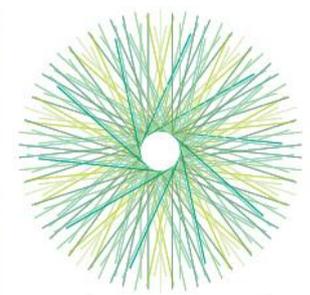
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