



# Qualitative and quantitative soil organic matter estimation for sustainable soil management

Jolanta Kwiatkowska-Malina<sup>1</sup>

Received: 28 July 2017 / Accepted: 5 December 2017 / Published online: 28 December 2017  
© The Author(s) 2017. This article is an open access publication

## Abstract

**Purpose** The aims of this paper were to review tools and methods for qualitative and quantitative evaluation of soil organic matter (SOM) coming from diverse exogenous sources for effective soil management, and to introduce a new approach to predict dynamics of SOM transformations, especially humification, as a key process in the formation of humic substances (HSs).

**Materials and methods** A review of existing literature is presented on tools and methods for qualitative and quantitative assessment of organic matter in soil originating from various sources for reasonable soil management, attempting to provide a better understanding of the advances in organic matter transformations and new research directions for modeling. Diverse tools and methods for qualitative and quantitative evaluation of organic matter in soil coming from diverse sources have been adopted so far to express transformation processes.

**Results and discussion** For the qualitative analysis of SOM and humic acids (HAs), the analytical techniques are applied, e.g., HPSEC, NMR, and ESI-FTICRMS. The quantitative analysis is done through the following parameters: humification index (HI), humification degree (HD), and humification rate (HR). These analyses indicated that because of lack of reliable data from sufficiently long-term experiments, mathematical modeling may be applied as a numerical tool for quantitative estimation and prediction of humification of SOM. The effective soil management should include soil properties as well as different functions: food production, nutrient and water cycling, storage, filtering, buffering, biological habitat, gene pool, source of raw materials, climate regulations, heritage, platform for man-made structure. The soil utility value should be evaluated through the SOM qualitative and quantitative analysis of organic carbon and total nitrogen. Knowledge about dynamics of SOM transformations is essential, particularly in the context of stability and efficiency of different sources of organic matter applied into soil. A qualitative understanding of SOM dynamics transformations along with modeling for quantitative assessment of HS formation should be used to develop sustainable soil management. The modeling may be considered as a tool for predicting SOM humification dynamics and consequently the formation of HSs from the diverse sources. The existing archival data from a long-term experiment may be used to build and calibrate the reliable mathematical model of SOM humification.

**Conclusions** Managing of SOM remains a sound basis for maintaining soil in a good condition for optimizing productivity. The development of land management strategies to optimize both the increase of soil organic carbon levels and the recycling of nutrients from SOM needs to be a priority. This should include policy makers and other users as well.

**Keywords** Humification · Mineralization · Soil organic matter · Sustainable management

---

Responsible editor: Yona Chen

✉ Jolanta Kwiatkowska-Malina  
jolanta.kwiatkowska@pw.edu.pl

<sup>1</sup> Department of Spatial Planning and Environmental Sciences, Warsaw University of Technology, Politechniki 1 Sq., 00-661 Warsaw, Poland

## 1 Introduction: importance of soil organic matter in sustainable soil management

Soil is largely a non-renewable resource and it provides the basis of ecosystems by performing many key environmental, social, and economic functions: food production (99%), nutrient and water cycling, storage, filtering and buffering,

biological habitat and gene pool, source of raw materials, climate regulations, physical and cultural heritage, platform for man-made structure (Blum 2005; Dominati et al. 2010; Banwart et al. 2017). Soil is extremely important as a filter removing pollution from water and helping to regulate the flow of water through the landscape (Rawls et al. 2003; Keesstra et al. 2012).

Soil organic matter (SOM) is responsible for the provision of these functions of soil nowadays and in the future (Craswell and Lefroy 2001; Leszczynska and Kwiatkowska-Malina 2011; Schmidt et al. 2011). It is a building block for the soil structure, acts as a large carbon sink in the biosphere, and plays an important role in the CO<sub>2</sub> balance. It is important both as a driver of climatic change and a response variable to climate change, capable of acting as a source and sink of carbon (Lal 2004a; Smith 2012). Soils also help to regulate other greenhouse gases such as nitrous oxide and methane (Muñoz et al. 2010; Oertel et al. 2016).

A decrease of SOM contents is among eight main threats for soils as indicated in the EU Soil Thematic Strategy (European Environment Agency 2010). Since the mid-nineteenth century, about 108 to 188 Pg C have been lost mostly from terrestrial biomass whereas about 25% of this loss is contributed to SOM mineralization (Zech et al. 1997; Lal 2004a; Houghton 2012). The losses of carbon from soil can be mitigated by recarbonization using management practices thereby increasing food security (Sauerbeck 2001; Lorenz and Lal 2012). Nevertheless, some mitigation options in agriculture are in direct competition with each other, e.g., use of crop residue for second-generation bioenergy crops versus residue inclusion into soil for maintenance or build-up of SOM (Shahbaz et al. 2017). The direction of changes and conversion of SOM nowadays is influenced by land management, especially for agricultural land. Soils easily and quickly lose organic carbon accumulated mainly as SOM (95%—pastures, meadows and 100%—arable land) when natural soils are converted into agricultural soils (Barancikova et al. 2016). It is estimated that soil cultivation, mainly conversion of pasture into arable land, leads to significant organic carbon losses (up to 50 Pg) in the overall balance (Janzen 2006). Information about broad ranges of SOM content is needed for general knowledge of changes in soil quality resulting from management practices that either favor among others soil erosion or accelerated SOM decomposition (Shibu et al. 2006).

SOM can be divided into three main pools: labile, stable, and inert (humins). Generally, it consists of two main fractions: humic substances—HSs (fulvic acids—FAs, humic acids—HAs, humins) and labile organic matter (Gonet et al. 2002; Strosser 2010). Humic substances (HSs) have been found to be a stable material, specific to each type of soil and not markedly changing over decades of soil use (Stevenson 1994).

Man has recognized the importance of organic amendments for maintaining or increasing the content of SOM since he started farming (Allison 1973; Reeves 1997; Scotti et al. 2015). It is, therefore, important to assess safe agricultural use of the exogenous organic matter as the fertilizer or conditioner of soil properties including an increase of SOM content. Organic substances more rich in carbon but poor in nitrogen (e.g., wood, tree coniferous, straw, brown coal) are relatively stable sources of energy and substrates for microorganisms, and can therefore be mineralized and humified relatively slowly (Zech et al. 1997; Kalbitz et al. 2000; Manzoni et al. 2010). This is consistent with the paradigm that improving production and environmental functions of the soil will lead to the increased quality of the environment.

With the above in mind, the paper presents a review of tools and methods for qualitative and quantitative evaluation of SOM coming from diverse sources for effective soil management that are currently important in international research. However, there are only few studies that address and assess the advances in modeling of organic matter transformations in soil.

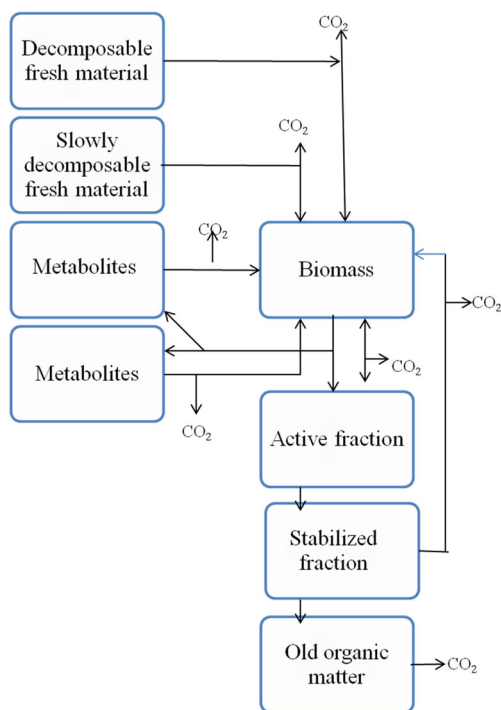
## 2 Stability of organic matter in soils

Due to many soil parameters determining soil functions, they are difficult to measure directly, especially over large areas. For these reasons, they are usually assessed by deriving and/or measuring indicators or proxies that correlate with soil conditions, and can be used to assess soil quality and its functioning. Some soil quality indicators are descriptive and can be used in the field while others are quantitative and must be assessed by laboratory analyses. There are three main categories of the soil indicators: chemical (e.g., nutritional status), physical (e.g., hydrological characteristics such as water retention by soil structure), and biological (e.g., soil respiration). Organic matter transcends all three categories of indicators as it is related to all soil functions and is itself an indicator of soil quality. Organic matter within the soil serves several functions. From a practical agricultural standpoint, it is important for two main reasons: (i) as an “evolving nutrient fund” and (ii) as an agent to improve soil structure, maintain tilt, and minimize erosion. SOM has been widely promoted as a key indicator of soil quality, particularly in agricultural soils, but there has been no consensus on what the critical level of it should be in an agricultural soil, and how this level will vary between soils of different textural classes under different environmental conditions. There are several different types of SOM as a result of the way of its formation. In general, three distinct types of SOM have been defined (Stevenson 1994; Six and Jastrow 2002): (i) decomposing plant residues, fungal hyphae, fine plant roots, and associated biomass which usually is unstable and has a short turnover time (< 1–2 years), (ii) an active

component that includes partially stabilized organic materials and microbial metabolites—usually referred to as the humus fraction (turn over time of 5–25 years), (iii) resistant fraction which is strongly stabilized either chemically or physically (turnover time of 250–2500 years). SOM while a relatively simple property to measure may be characterized in many different ways (Nortcliff 2002; Jones et al. 2005). The different methods of measuring SOM and soil carbon are based on detecting different organic materials (Conyers et al. 2011).

An organic material, largely plant material, in the initial stages of transformation, is composed of complex carbohydrates (celluloses, polysaccharides), plant proteins (high nitrogen content), cuticular waxes, lipids, and lignin. The resistance of the components within initial transformation of organic materials (from least to most stable) is as follows: simple sugars < amino acids < proteins < cellulose < hemicellulose < fats, starches, and waxes < lignin and tannins. These compounds undergo decomposition releasing CO<sub>2</sub> (Fig. 1).

Understanding of qualitative and quantitative changes of SOM is crucial for agronomic aspects like nutrient dynamics, structure, and water storage capacity, as well as for environmental issues such as biodiversity, nitrate leaching, and carbon storage (Schnitzer et al. 2006). A small part in spite of many works about quality of soil quantitative, estimate only directly, according to Nortcliff (2002), it reflects the difficulty of finding such conducting of reliable index (parameters).



**Fig. 1** Flow chart for transfer of C involved in the mineralization and immobilization processes

The classification of soil HSs proposed by Stevenson (1994) is based entirely on operational procedures which say that the humin fraction may consist of one or more compound classes including paraffinic substances. Nowadays, thanks to separation and fractionation techniques the isolation and identification of components plentiful in carbohydrates and amino acids and a humin fraction rich in aliphatic carbon is possible. Burdon (2001) referred to the spectroscopic data which show, e.g., that lignin is a major contributor to the aromaticity of HSs. According to Sutton and Sposito (2005), HSs are collections of diverse, relatively low molecular mass components forming dynamic associations stabilized by hydrophobic interactions and hydrogen bonds. Nebbioso et al. (2016) used the humeomics approach to obtain humeome fractions analyzed by high-performance size exclusion chromatography (HPSEC), which were classified according to molecular weight and degree of unsaturation as well as oxygen and nitrogen contents in formulae (Hayes and Swift 2017).

The contribution of lignin to soil humic components is still discussed. Although based on electrospray ionization Fourier transform ion cyclotron resonance mass spectrometry (ESI-FTICRMS) data, it was shown that carboxylic acids bound to both aliphatic and condensed aromatic molecules are common components of HAs (DiDonato and Hatcher 2016; DiDonato et al. 2016). In their opinion, the vicinities of a variety of carboxylic groups to an assortment of structural components would indicate that “lignin-like” compounds represent the third major molecular group common to HAs (DiDonato et al. 2016).

Using solid-state two-dimensional <sup>1</sup>H-<sup>13</sup>C correlation NMR spectrometry, Cao et al. (2016) proposed primary and secondary structures for a lignite HA fraction. According to Leenheer (2016), HSs are polyphenolic polycarboxylic acids derived from lignin and tannins, and these would form electron-rich (nucleophilic) cavities between stacked aromatic rings at low pH values. This novel approach could provide an interpretation of how naturally occurring and anthropogenic organic chemicals might be bound in SOM.

To evaluate quantitatively SOM and HSs, the following parameters could be applied among others (Sequi et al. 1986; Cavani et al. 2003): humification index (HI), humification degree (HD), and humification rate (HR).

$$HI = NH / (HAs + FAs)$$

$$HD = 100 \times (HAs + FAs) / TEC$$

$$HR = 100 \times (HAs + FAs) / TOC$$

where NH—contents of fraction, which was not humified (g), HAs—humic acids (g), FAs—fulvic acids (g), TEC—total extracted carbon (g), and TOC—total organic carbon (g).

Data for this evaluation could be obtained from long-term field experiments.

### 3 Numerical tools useful for management of soil organic matter

Prior to describing the dynamics of SOM, the terminology should be clarified such as carbon turnover, transformation, net decomposition, humification, and mineralization (Shibu et al. 2006). Carbon turnover in general includes mineralization and transfer from one pool to another, containing microbial biomass. Transformation is the process in which a substrate is transformed into organic compounds and CO<sub>2</sub>, whereas net decomposition accounts for the CO<sub>2</sub> component only (Van Keulen 2001). During humification, carbon from organic residues is converted to HSs through biochemical and abiotic processes, whereas mineralization leads to the conversion of organic carbon to CO<sub>2</sub> and is, therefore, similar to net decomposition.

Rate equations for transformation of various SOM pools are described by zero-order, first-order, or Michaelis-Menten (Monod) kinetics (Shibu et al. 2006). The process described by zero-order kinetic proceeds at a constant rate, independent of the substrate (C) concentration:

$$dC/dt = -k_0,$$

while the rate of a first-order reaction is proportional to the substrate concentration:  $dC/dt = -k_1C$ .

In Monod-type kinetics, the reactions are described as biological processes with rates depending on the amount of microbial biomass which is involved in the utilization of a substrate:

$$dC/dt = -dC/dt_{(max)}C/(K_c + C)$$

where  $k_0$  is the rate constant for a zero-order reaction,  $k_1$  is the relative rate constant for a first-order reaction, and  $K_c$  represents the half-saturation concentration. The rate is equal to half of the maximum ( $(dC/dt)_{(max)}$ ), defined as a function of microbial biomass.

The studies of genesis of HSs initiated by Williams were concluded by Konoova (1966) that these were (i) humus substances exist in soil as a natural body, (ii) various plant materials which undergo complex biochemical transformations serve as sources of humus substances, (iii) plant materials decompose to more simple products from which the complex HSs are synthesized, and (iv) and microbial enzymatic activity is involved in both the decomposition and the synthesis processes (Hayes and Swift 2017).

At any given time, HSs consist of a range of materials: from the intact original tissues of plants and animals to the substantially decomposed mixtures (Yang and Janssen 2000). SOM is in different stages of biochemical and microbiological transformations, as a result of enzymatic activity of microorganisms (among others fungi and bacteria) as a result of mineralization and humification processes (Chen and Inbar 1993).

Some scientists consider the synthesis of HSs to be entirely biological, but there is a growing concept suggesting that the compounds released in the microbial breakdown of organic substrates could condense to give rise to humic products from chemical synthesis processes. However, such structures as humic-type substances are not formed in soil under biological conditions; they could arise from char coming from burning vegetation or amendments containing biochar (Hayes and Swift 1978; Clapp et al. 2005).

In recent years, the view is that organic materials in soils are transformed (humified) into (i) amorphous polymeric, HAs, FAs, and humins and (ii) compounds belonging to recognizable classes, such as carbohydrates, peptides, altered lignins, fats, waxes, cutins, and cutans. These can be synthesized by microorganisms or can arise from alterations of similar materials in the original debris (Hayes and Swift 2017). Nevertheless, according to Lehmann and Kleber (2015), SOM is a “continuum of progressively decomposing organic compounds”, so they would not agree with the concepts of HAs, FAs, and humins.

At present, it can be stated that humification comprises progressive transformations of organic debris, and at some stage during the transformation processes, products are formed that satisfy the definitions for HAs and FAs. These fractions can be further stabilized and retained through associations with the soil clays and the divalent and polyvalent cations, as well as with the oxide minerals, in particular those of aluminum, iron, and manganese (Hayes and Swift 2017). It is unlikely that it will ever be possible to determine a definitive, detailed structure of a single, specific, isolatable “humic compound” or molecule.

Humification is a continuous process, but, given sufficient time, a stage is reached when the degree of transformation is such that there is little or no evidence of decomposed materials (Wadman and de Hann, 1997; Rumpel et al. 1999). According to Hayes and Swift (2017), the materials isolated from composts, sewage sludge or from putrefying materials, should not be regarded as such until these have undergone considerable transformations in soil.

From the mid-1970s, improved computing facilities and better understanding of the processes led to rapid development of dynamic SOM models (Frissel and Van Veen 1981). There are analytical, comprehensive, and summary models (Shibu et al. 2006). Analytical models mostly consider SOM as a single homogenous pool that decomposes with relative rates varying in time. Henin and Dupuis (1945) were among the first to quantitatively describe SOM dynamics. They stated that fresh organic material added to the soil would decline. Kortleven (1963) in addition to Henin and Dupuis (1945) concept assumed that conversion of fresh organic matter into humus can be represented by two constants: the fraction of organic material remaining in the soil after 1 year (i.e., the humus fraction or humification coefficient) and the relative

decomposition rate of the humus. Both appeared dependent on the type of organic material used. Kolenbrander (1969) modified the Henin and Dupuis (1945) model, considered as a single pool of total organic matter however, with a relative decomposition rate decreasing with time. On the basis of long-term decomposition experiments with the  $^{14}\text{C}$ -labeled plant material in soils of the temperate and tropical origin, Sauerbeck and Gonzalez (1977) concluded that during the first year, 65% of the added material disappeared, and stable residues and turnover products followed an exponentially decreasing function. These results suggest the existence of two independent organic fractions: (i) an easily decomposable labile fraction and (ii) a more resistant stable fraction. Combining labile and stable organic matter fractions, Janssen (1984) proposed to introduce the relative rate of decomposition which was defined as an empirical function of the “initial age” of the organic material. For theoretical analysis of natural ecosystems and simulation of SOM mineralization, humification, and nitrogen release, Chertov and Komarov (1996, 1997) developed the soil organic mineralization model (SOMM). The model consists of variable coefficients: the litter input rate, the non-decomposed part of the litter remaining in the soil, the complex humic substance with non-decomposed plant debris, and the humus content. For long-term predictions of carbon dynamics in soil to estimate carbon sequestration capacity, the introductory carbon balance model (ICBM) has been defined (Andrén and Kätterer 1997). The effect of climatic factors was condensed into a single parameter that similarly affects the decomposition rates of “young” and “old” organic matter. This parameter needs to be optimized for a particular ecosystem based on experimental or available literature data. The value of humification rate is defined depending on the litter quality and external factors such as soil type.

Parnas (1975) applied a process-based modeling approach to simulate SOM dynamics. The models consider SOM as heterogeneous mixtures, and decomposition of components in this mixture, represented by a number of arbitrary pools, takes place at different relative rates. These models were divided into comprehensive and summary models. Generally, the comprehensive model has been designed for research purposes whose essential elements are thoroughly understood (Penning de Vries 1982). The production of annual pasture limited by the rainfall and nitrogen model (PAPRAN) distinguishes two fractions of SOM (Seligman and Van Keulen 1981): fresh (simple sugars, cellulose/hemicellulose, lignin) and stable. The decomposition rate of an organic material is based on the first-order kinetics and depends on soil temperature, soil moisture, and C/N ratio of the substrate. The relative rate of decomposition declines sequentially with increasing C/N ratio as more easily decomposable fractions vanish. Juma and Paul (1981) tested the concepts of soil microbial growth and decay to study mineralization and immobilization

of soil N assuming that SOM is resented by active, stabilized, and old pools. The active pool was further sub-divided into biomass, active, and metabolites, while the passive pool into a stabilized component and an old pool with half-lives of around 35 and 600 years, respectively. During decomposition of carbon substrates, a portion of the carbon is transferred to the microbial biomass pool and the remaining part is released as  $\text{CO}_2$ . Microbial biomass undergoes decomposition and decay, 50% of the products goes to the active pool and the rest to the metabolite pool. Both pools also undergo decomposition and are transformed into biomass, while  $\text{CO}_2$  is released. Part of the active carbon transferred to the stable pool is subsequently transferred to the old pool. The multi-layer, multi-component model, with varying numbers of soil layers and six organic carbon pools, was proposed by Van Veen and Frissel (1981). The decomposition rate of SOM is controlled by the uptake of carbon by microbial biomass. Nitrogen and carbon transformation in soil (NCSOIL) is a module of a model describing C and N flows in the soil-water-air-plant system (NCSWAP) (Molina et al. 1983). In this model, SOM was divided into fresh plant residues, microbial biomass, and labile and stable organic pools. Decomposition of the pools proceeds independently with relative rates that fall below the potential when not enough nitrogen is available for the growing of microbial biomass. The ECOSYS (Ecosystem) model developed by Grant (2001) for natural and managed ecosystems simulates processes of soil water, heat, carbon, oxygen, nitrogen, phosphorus transport, and gaseous ( $\text{CO}_2$ , methane,  $\text{N}_2\text{O}$ ) exchanges with a range of management options (tillage and residue management). Each organic state in each substrate-microbe complex was further divided into carbohydrate, cellulose, and lignin with varying rates of relative decomposition. Residue decomposition products undergo humification. A fraction of lignin coupled with proteins and carbohydrates is transferred to the solid substrate of active SOM. Products of microbial decomposition are divided between microbial residues, and the solid substrate of the passive SOM substrate-microbe complexes depends on the soil clay content.

Summary models are more suitable for applicative and predictive purposes where essential aspects of comprehensive models are formulated in less detail (Van Ittersum et al. 2002). RothC (Rothamsted carbon) is a transformation model that simulates the turnover of organic carbon in non-waterlogged soils in monthly time intervals and allows for the effects of soil type, temperature, moisture content, and plant cover (Coleman and Jenkinson 1996). In this model, SOM was divided into five components with different decomposition rates. Many concepts in the RothC model are similar to Van Veen and Paul's (1981) and CENTURY models (Patron et al., 1992). The latter is the SOM model to which a crop growth module has been added. The model simulates the dynamics of carbon, nitrogen, phosphorus, and sulfur for

different plant production systems such as grassland, arable land, forests, and savannas. Metabolic and cellulose carbon is transferred to the active pool while lignin C goes directly to the slow pool. The actual relative rate of the structural pool of decomposition is derived from its lignin content, whereas for the active pool, it is modified for soil texture, soil temperature, and the moisture content. This model needs very precise input data acquisition of which is a problem for all agricultural soils in a specific region or country (Barančíková et al. 2016). Field data at diverse temporal and spatial (local/regional) scales are important to obtain the reliable model (Ouyang et al. 2017). The Verberne model (Verberne et al. 1990) describes carbon and nitrogen cycling in different soil types, with the objective of predicting the daily net rate of mineralization. The model divides organic material into three pools of residues and four pools of SOM, based on biochemical composition, the C/N ratio, and the lignin content. The carbon and nitrogen dynamics (CANDY) model allows for specification of up to six categories of fresh organic matter, including manure and/or slurry (Franko et al. 1995). It distinguishes three sets of pools: fresh organic matter (FOM), biologically active organic matter (BOM), and slow cycling SOM. Carbon moves out of each pool with rate constants adjusted for the effect of temperature, soil water content, and soil aeration. The remainder being released as CO<sub>2</sub>. The SOCRATES model estimates changes in soil organic carbon (SOC) as influenced by the cropping pattern, including pastures (Grace and Ladd 1995). The main advantage in its development was that the input data could be easily measured in the laboratory. At the beginning, 2% of the measured SOC is assumed to be protected and the remaining 98% is defined as stable humus. Carbon was transferred to the microbial biomass, humus, and CO<sub>2</sub>—the relative decomposition rates for each of the components were calculated using <sup>14</sup>C data.

Most modern SOM dynamics models have focused on the mineralization processes (mainly microbial heterotrophic respiration) and have not included the effects of soil fauna that are known as key agents of SOM formation. Komarov et al. (2016) developed a modeling approach predicated on the existence of definable stoichiometric relations among the processes leading to SOM formation that are mediated by soil biota. They developed a food web-based module, using a synthesis of decades of published data, to describe the micro- and meso-faunal excrement and necro-mass production. As well as they developed a separate module for anecic earthworms (i.e., those that have vertical borrows and produce surficial earthworm casts), with explicit representation of processes related to fresh casts. These two modules were compiled and integrated in the ROMUL model of SOM dynamics without changing the structure of the original model. These modules enabled calculation of the proportional contribution of faunal by-products to humification and carbon sequestration. Testing the new version known as the Romul Hum model showed

consistent accumulation of faunal by-products in the “final” SOM fractions (Komarov et al., 2016). The main improvement of the Romul Hum model is that the by-products of soil micro- and meso-fauna, and their role as precursors to formation of stable SOM, are included. The ratios of “excrement mass/necro-mass C to soil heterotrophic respiration C” were key parameters introduced into the Romul Hum model. This novel approach to including soil faunal activity in modeling of soil C dynamics takes advantage of the high degree of organization within soil biotic communities in food webs, and it integrates the effects of microorganisms and soil fauna that govern the processes of organic residue transformation and mineralization in the soil system (Chertov et al. 2017a). Quantitative description of the role of soil fauna in SOM formation and dynamics is necessary for further development of modeling. The eco-physiological parameters of food consumption, excretion efficiency, assimilation efficiency, lifespan, and mortality for anecic earthworms were developed using an approach similar to that for food web meso-fauna in the Romul Hum model. The addition of the earthworm module to the Romul Hum model allows for assessment of the combined effects of earthworm cast production and micro- and meso-faunal food web activity within the casts, on the formation of stable SOM (Chertov et al. 2017b). Some of the SOM transformation models described above are summarized in Table 1. Reliable quantitative evaluation of the formation of HSs using, e.g., the parameters such as HI, HD, and HR requires data from long-term experiments which are lacking because they are usually costly and time consuming. Therefore, mathematical modeling may be considered as a tool for predicting SOM humification dynamics and consequently the formation of HSs from the diverse sources. On the other hand, reliable models require input data preferably from a long-term experiment. To overcome this inconvenience, the existing archival data from a long-term experiment may be used to build and calibrate the mathematical model of SOM humification for this particular case. Then the developed model needs to be validated based on data obtained from the running short-term test to evaluate quantitatively HS formation in this new case.

#### 4 Sustainability of soil management

Soil is mostly non-renewable, one of the most important parts of the natural environment. While not widely appreciated by most people, soil is actually at the center of nearly all terrestrial processes. All economies as well as high living standards depend on goods and services provided by the environment, mainly the soil. Land and soil are vital for society to meet its needs for food, drinking water, energy, shelter, and infrastructure. Many of society’s environmental challenges, such as climate change, depletion of natural resources, and loss of

**Table 1** Summary of studies reporting SOM transformation models

Model	C pools	Type	References
PAPRAN	Fresh Stable	Comprehensive	Penning de Vries 1982
NCSOIL	Residue pool Pool labile Pool I resistant Pool II labile Pool II resistant Pool III (stable humus)	Comprehensive	Molina et al. 1983
CENTURY	Structural Metabolic Active SOM Slow SOM Passive SOM	Summary	Patron et al., 1992
CANDY	Fresh organic matter Biologically active SOM Slow cycling SOM	Summary	Franko et al. 1995
SOCRATES	Decomposable plant material Resistant plant material unprotected MB Protected MB Stable OM	Summary	Grace and Laad 1995
RothC	Decomposable plant material Microbial biomass Resistant plant material Humus Inert organic matter roots Litter Faces	Summary	Coleman and Jenkinson 1996
SOMM	Undecomposed litter Litter impregnated by humic substances Humic substances of mineral top soil	Analytical	Chertov and Komorov 1996, 1997
ICBM	Young Old	Analytical	Andren and Katterer 1997
ECOSYS	Plant residue Animal manure Particulate (active) Non-particulate (passive) organic matter Microbial residue	Comprehensive	Grant 2001
ROMUL	Stable SOM	Summary	Komarov et al. 2016

biodiversity, are related to the use of rural and urban land and soil. Many stakeholders (drinking water and energy producers, distributors, and suppliers; spatial planners, consultants, brownfield developers, and remediation contractors; farmers, foresters, and food companies; citizens; financiers; policy makers and regulators) are involved in making balanced and sustainable land use and land management decisions.

Sustainable soil management means temporal and/or spatial harmonization in the uses of key environmental, social, and economic functions, excluding or minimizing irreversible ones, which is not a scientific but a political task (Blum 2005).

The importance of organic matter in soil is not a recent discovery. The maintenance of SOM levels in arable soils is crucial for sustainable crop production for soil and climate protection and mitigation strategies (Freibauer et al. 2004;

Lal 2004b; Janzen 2004, 2005; Bellamy et al. 2005; Johnston et al. 2009; Leithold et al. 2015). Furthermore, SOM is a relevant accumulator and transformer of nutrients (Fageria 2012). Simultaneously, in contrast to soils' calculated potentials to sequester carbon, arable soils currently lose carbon in many regions (Janssens et al. 2005; Kutsch et al. 2010; Schrumpf et al. 2011). Cultivation of soils usually causes a decrease of the organic matter content. For most soils, a high level of organic matter is maintained only by grass species. In agriculture, increasing soil organic carbon content is often seen as a desirable objective, especially in organic farming (Mader et al. 2002; Lal et al. 2004; Yigini and Panagos 2016), though the benefits of organic C in soil in terms of fertility arise in part from its decay and not from its accumulation (Janzen 2004). Sequestration of C in soils and low-carbon technologies have also been promoted as a strategy to mitigate the effects of increasing emissions of greenhouse gases in the atmosphere (Lal 2001; Janzen 2004; Minasny et al. 2017).

With regard to soil key functions and services, including carbon sequestration, losses of SOM cannot be accepted. Therefore, tools for a reliable assessment of the state of exogenous organic matter supply to soils in farming practice are required. Balance of SOM has been approved as a practice-applicable approach to the assessment of SOM management (Brock et al. 2013; Bila et al. 2016). Man has recognized the importance of organic amendments for maintaining or improving the content of SOM since he started farming. Soil fertility in early agricultural systems was based on the recycling of organic wastes. There have been vast changes in the nature of agricultural production. In the past, farms were small and much of what was produced was consumed on the farm. This system allowed for the limited removal of soil nutrients since there was an opportunity to return most of them back to the land. As a result, among others, migration from rural to urban communities, increased farm sizes, and specialization in production have changed a system of production in such a way that there is higher removal of nutrients from the soil and less opportunity for nutrient cycling. In Poland, occurring soil species (predominantly sandy soils) and an inadequate land management have led to reduction of the organic matter contents in soils. This effect is intensified by the limited availability and high cost of conventional sources of applied organic matter such as farm manures or crop residues and the popular use of mineral fertilizers. Therefore, new sources of organic matter have been tapped such as municipal solid waste compost, brown coal of low energetic value, sewage sludge, biochar, and brown coal preparations (Drozd 2003; Kwiatkowska et al. 2008; Sohi et al. 2010; Leszczyńska and Kwiatkowska-Malina, 2011; Usman et al. 2012; Ouyang et al. 2014; Novotny et al. 2015).

Concerning the nutrient cycling, there is a potential conflict in terms of the management of SOM. One objective may be to

increase soil organic and soil carbon levels while the second goal is to ensure adequate N, P, and S nutrition for crops and pastures (Janzen 2006). The utilization of the nutrient pool in SOM requires its mineralization which by definition requires the break down and reduction of the SOM pool in the soil. While this does not necessarily mean that both objectives cannot be met by well-balanced and strategic management, it is a fundamental conflict requiring the development of specialized management strategies. The key would appear to be in the development of management strategies that ensure rapid nutrient cycling and take full advantage of the capacity of legumes to fix N. This immediately brings the system under a potential acidification pressure which needs to be managed. Hence, there is a need for finely balanced management systems.

There is a link between the build-up of SOM, the fixation of N by legumes, and the need for adequate P nutrition (Chan et al. 2010). The impact of SOM on productivity is complex because it affects a range of soil properties, not a single property. It seems to relate very well to the overall effects of soil organic matter on productivity (Watt et al. 2006). SOM can influence a number of soil properties and, therefore, potentially a wide range of soil functions. By influencing a range of functions, the effects of SOM can be substantial. The most practical way to improve soil quality is to promote better management of SOM including soil carbon.

Managing SOM remains a sound basis for maintaining soil in a good condition for optimizing productivity and maintaining the productive capacity of soil in the long term. The development of land management strategies to optimize both the increase of soil organic carbon levels and the recycling of nutrients from SOM needs to be a priority. Soil organic carbon sequestration can make soils a sustainable resource, not a renewable resource (Minasny et al. 2017).

## 5 Conclusions

Land and soil are vital for society to meet its needs for food, drinking water, energy, shelter, and infrastructure. Soil organic matter (SOM) is responsible for the provision of these functions of soil nowadays and in the future. Although analytical methods are widely used to evaluate changes in soil management or organic carbon turnover, the practical question of the quantity and quality of SOM cannot be answered completely. The development of the parameterization system of SOM quality and quantity could assist more rational and sustainable management of the soils. The effective soil management should include its properties as well as different functions: food production (99%), nutrient and water cycling, storage, filtering and buffering, biological habitat and gene pool, source of raw materials, climate regulations, physical and cultural heritage, platform for man-made structure. Organic



matter in soil has been widely promoted as a key indicator of soil quality, particularly in agriculture. There are several different types of SOM as a result of the way of its formation. Understanding of qualitative and quantitative changes of SOM is crucial for agronomic aspects like nutrient dynamics, structure, and water storage capacity. The fundamental conflict between increasing soil organic carbon and using the mineralization of SOM as a source of nutrients requires further investigation and resolution. The modeling of nutrient cycling across seasons, locations, and soil types would be a one of recommendation. Nowadays, for the qualitative analysis of SOM and humic acids (HAs), the analytical techniques are applied, e.g., HPSEC, NMR, and ESI-FTICRMS. A qualitative understanding of SOM dynamics transformations along with numerical modeling for quantitative assessment of HS formation should be used to develop sustainable soil management. The quantitative analysis is done through the following parameters: humification index (HI), humification degree (HD), and humification rate (HR). For better understanding of transformation of SOM, there are used analytical, comprehensive, and summary dynamic models. Summary models are more suitable for applicative and predictive purposes where essential aspects of comprehensive models are formulated in less detail. Therefore, mathematical modeling may be considered as a tool for predicting SOM humification dynamics and consequently the formation of HSs from the diverse sources. The existing archival data from a long-term experiment may be used to build and calibrate the reliable mathematical model of SOM humification. Then the developed model needs to be validated based on data obtained from the running short-term test to evaluate quantitatively HS formation. Dynamics of SOM transformations is important, especially in the context of stability and efficiency of organic matter sources applied into soil. The soil utility value should be evaluated through the SOM qualitative-quantitative analysis of organic carbon and total nitrogen. Managing of SOM remains a sound basis for maintaining soil in a good condition for optimizing productivity and maintaining the productive capacity of soil in the long term. The development of land management strategies to optimize both the increase of soil organic carbon levels and the recycling of nutrients from SOM needs to be a priority. This should include policy makers and other users as well.

### Compliance with ethical standards

**Conflict of interest** The author declares that he/she has no conflicts of interest.

**Open Access** This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

### References

- Allison FE (1973) Soil organic matter and its role in crop production. Elsevier Science, New York
- Andr n O, K tterer T (1997) ICBM—the introductory carbon balance model for exploration of soil carbon balances. *Ecol Appl* 7(4): 1226–1236. [https://doi.org/10.1890/1051-0761\(1997\)007\[1226:ITICBM\]2.0.CO;2](https://doi.org/10.1890/1051-0761(1997)007[1226:ITICBM]2.0.CO;2)
- Banwart SA, Bernasconi SM, Blum WEH, de Souza DM, Chabaux F, Duffy C, Kercheva M, Kr m P, Lair GJ, Lundin L, Menon M, Nikolaidis NP, Novak M, Panagos P (2017) Quantifying and managing soil functions in Earth’s critical zone—combining experimentation and mathematical modelling. Chapter one—soil functions in Earth’s critical zone: key results and conclusions. *Adv Agron* 142:1–27. <https://doi.org/10.1016/bs.agron.2016.11.001>
- Baran nkov  G, Makovnikov  J, Halas J (2016) Effect of land use change on soil organic carbon. *Agriculture (Poľnohospod rstvo)* 62(1):10–18
- Bellamy M, Loveland PJ, Bradley RI, Lark RM, Kirk JD (2005) Carbon losses from all soils across England and Wales. 1978–2003. *Nature* 437(7056):245–248. <https://doi.org/10.1038/nature04038>
- Bila P, Sarapatka B, Cap L (2016) The influence of type, composition and dosage of exogenous organic matter on selected biochemical soil properties. *Soil Water Res* 11(4):220–227
- Blum WEH (2005) Functions of soil for society and the environment. *Rev Environ Sci Biotechnol* 4(3):75–79. <https://doi.org/10.1007/s11157-005-2236-x>
- Brock C, Franko U, Oberholzer H-R, Kuka K, Leithold G, Kolbe H, Reinhold G (2013) Humus balancing in Central Europe—concepts, state of the art, and further challenges. *J Plant Nutr Soil Sci* 176(1): 3–11. <https://doi.org/10.1002/jpln.201200137>
- Burdon J (2001) Are the traditional concepts of the structures of humic substances realistic? *Soil Sci* 166(11):752–769. <https://doi.org/10.1097/00010694-200111000-00004>
- Cao X, Drosos M, Leenheer JA, Mao J (2016) Secondary structures in a freeze-dried lignite humic acid fraction caused by hydrogen bonding of acidic protons with aromatic rings. *Environ Sci Technol* 50(4): 1663–1669. <https://doi.org/10.1021/acs.est.5b02859>
- Cavani L, Ciavatta C, Gessa C (2003) Identification of organic matter from peat, leonardite and lignite fertilizers using humification parameters and electrofocusing. *Bioresour Technol* 86(1):45–52. [https://doi.org/10.1016/S0960-8524\(02\)00107-4](https://doi.org/10.1016/S0960-8524(02)00107-4)
- Chan KY, Oates A, Li GD, Conyers MK, Prangnell RJ, Polie G, Liu DL, Barchia IM (2010) Soil carbon stocks under different pastures and pasture management in the higher rainfall areas of south-eastern Australia. *Aust J Soil Res* 48(1):7–15. <https://doi.org/10.1071/SR09092>
- Chen Y, Inbar Y (1993) Chemical and spectroscopical analyses of OM transformations during composting in relation to compost maturity. In: Hoitnik HAJ, Keener HM (eds) . Science and engineering of composting renaissance publications, Worthington, OH, pp 551–600
- Chertov OG, Komarov AS (1996) A model of soil organic matter and nitrogen dynamics in terrestrial ecosystems. In: Powlson DS, Smith P, Smith JU (eds) Evaluation of soil organic matter models using existing long-term datasets, Proceedings of the NATO advanced research workshop, NATO ASI series I, vol 38. Springer-Verlag, Berlin, pp 231–236. [https://doi.org/10.1007/978-3-642-61094-3\\_16](https://doi.org/10.1007/978-3-642-61094-3_16)
- Chertov OG, Komarov AS (1997) SOMM—a model of soil organic matter dynamics. *Ecol Model* 94(2-3):177–190. [https://doi.org/10.1016/S0304-3800\(96\)00017-8](https://doi.org/10.1016/S0304-3800(96)00017-8)
- Chertov O, Komarov A, Shaw C, Bykhovets S, Frolov P, Shanin V, Grabarnik P, Pripulina I, Zubkova E, Shashkov M (2017a) Romul\_Hum—a model of soil organic matter formation coupling with soil biota activity. II. Parameterisation of the soil food web

- biota activity. *Ecol Model* 345:125–139. <https://doi.org/10.1016/j.ecolmodel.2016.10.024>
- Chertov O, Shaw C, Shashkov M, Komorov A, Bykhovets S, Shanin V, Grabarnik P, Frolov P, Kalinina O, Pripulina I, Zubkova E (2017b) Romul\_Hum—a model of soil organic matter formation coupling with soil biota activity. III. Parameterisation of earthworm activity. *Ecol Model* 345:140–149. <https://doi.org/10.1016/j.ecolmodel.2016.06.013>
- Clapp CE, Hayes MHB, Simpson AJ, Kingery WL (2005) Chemistry of soil organic matter. In: Tabatabai MA, Sparks DL (eds) *Chemical processes in soils*. Soil Sci Soc Amer Inc, Madison, pp 1–150
- Coleman K, Jenkinson DS (1996) RothC-26.3—a model for the turnover of carbon in soil. In: Powlson DS, Smith P, Smith JU (eds) *Evaluation of soil organic matter models using existing long-term datasets*, Proceedings of the NATO advanced research workshop, NATO ASI series I, vol. vol 38. Springer-Verlag, Berlin, pp 237–246. [https://doi.org/10.1007/978-3-642-61094-3\\_17](https://doi.org/10.1007/978-3-642-61094-3_17)
- Conyers MK, Poile GJ, Oates AA, Waters D, Chan Y (2011) Comparison of three carbon determination methods on naturally occurring substrates and the implication for the quantification of ‘soil carbon’. *Aust J Soil Res* 49(1):27–33. <https://doi.org/10.1071/SR10103>
- Craswell ET, Lefroy RDB (2001) The role and function of organic matter in tropical soils. *Nutr Cycl Agroecosyst* 61(1/2):7–18. <https://doi.org/10.1023/A:1013656024633>
- DiDonato N, Hatcher P (2016) Multi-dimensional NMR and ESIFTICRMS analysis of soil humic acid: an investigation of aliphatic carboxylic acids. Proc 18th Inter'l IHSS Conf, Kanazawa, Japan
- DiDonato N, Chen H, Waggoner D, Hatcher PG (2016) Potential origin and formation for molecular components of humic acids in soils. *Geochim Cosmochim Acta* 178:210–222. <https://doi.org/10.1016/j.gca.2016.01.013>
- Dominati E, Patterson M, Mackay A (2010) A framework for classifying and quantifying the natural capital and ecosystem services of soils. *Ecol Econ* 69(9):1858–1868. <https://doi.org/10.1016/j.ecolecon.2010.05.002>
- Drozd J (2003) The risk and benefits associated with utilizing composts from municipal solid waste (MSW) in agriculture. In: Lynch JM, Schepers JS, Unver I (eds) *Innovative soil-plant systems for sustainable agricultural practices*. Organisation for Economic Co-operation and Development (OECD), Paris, pp 211–226
- European Environment Agency (2010) *The European environment: state and outlook 2010—soil*
- Fageria NK (2012) The role of soil organic matter in maintaining sustainability of cropping systems. *Commun Soil Sci Plant Anal* 43(16):2063–2113. <https://doi.org/10.1080/00103624.2012.697234>
- Franko U, Oelschlägel B, Schenk S (1995) Simulation of temperature, water and nitrogen dynamics using the model CANDY. *Ecol Model* 81(1-3):213–222. [https://doi.org/10.1016/0304-3800\(94\)00172-E](https://doi.org/10.1016/0304-3800(94)00172-E)
- Freibauer A, Rounsevell MDA, Smith P, Verhagen J (2004) Carbon sequestration in the agricultural soils of Europe. *Geoderma* 122(1):1–23. <https://doi.org/10.1016/j.geoderma.2004.01.021>
- Frissel MJ, Van Veen JA (1981) Simulation of nitrogen behaviour of soil-plant systems. Papers of a workshop: models for the behaviour of nitrogen in soil and uptake by plant. Comparison between different approaches. Pudoc, Wageningen
- Gonet SS, Debska B, Pakula J (2002) The content of dissolved organic carbon in soils and organic fertilizers. PTSH, Wrocław
- Grace PR, Ladd JN (1995) SOCRATES (soil organic carbon reserves and transformations in agro-eco-systems). CRC for Soil and Land Management, Adelaide
- Grant RF (2001) A review of the Canadian ecosystem model—ecosys. In: Grant RF (ed) *Modeling carbon and nitrogen dynamics for soil management*. Lewis Publishers, Boca Raton, pp 173–263. <https://doi.org/10.1201/9781420032635.ch6>
- Hayes MHB, Swift RS (1978) The chemistry of soil organic colloids. In: Greenland DJ, Hayes MHB (eds) *The chemistry of soil constituents*. Wiley, Chichester, pp 179–320
- Hayes MHB, Swift RS (2017) An appreciation of the contribution of Frank Stevenson to the advancement of studies of soil organic matter and humic substances. *J Soils Sediments*. pp 1–20. <https://doi.org/10.1007/s11368-016-1636-6>
- Henin S, Dupuis M (1945) Essai de bilan de la matière organique du sol. *Ann Agron* 15:17–29
- Houghton RA (2012) Historic changes in terrestrial carbon storage. Recarbonization of the biosphere. pp 59–82. [https://doi.org/10.1007/978-94-007-4159-1\\_4](https://doi.org/10.1007/978-94-007-4159-1_4)
- Janssen BH (1984) A simple method for calculating decomposition and accumulation of ‘young’ soil organic matter. *Plant Soil* 76(1-3):297–304. <https://doi.org/10.1007/BF02205588>
- Janssens IA, Freibauer A, Schlamadinger B, Ceulemans R, Ciais P, Dolman AJ, Heimann M, Nabuurs G-J, Smith P, Valentini R, Schulze E-D (2005) The carbon budget of terrestrial ecosystems at country-scale—a European case study. *Biogeosciences* 2(1):15–26. <https://doi.org/10.5194/bg-2-15-2005>
- Janzen HH (2004) Carbon cycling in earth systems—a soil science perspective. *Agric Ecosys Environ* 104(3):399–417. <https://doi.org/10.1016/j.agee.2004.01.040>
- Janzen HH (2005) Soil carbon: a measure of ecosystem response in a changing world? *Can J Soil Sci* 85(Special Issue):467–480. <https://doi.org/10.4141/S04-081>
- Janzen HH (2006) The soil carbon dilemma: shall we hoard it or use it. *Soil Biol Biochem* 38(3):419–424. <https://doi.org/10.1016/j.soilbio.2005.10.008>
- Johnston AE, Poulton PA, Coleman K (2009) Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. *Adv Agron* 101:1–57. [https://doi.org/10.1016/S0065-2113\(08\)00801-8](https://doi.org/10.1016/S0065-2113(08)00801-8)
- Jones C, McConnell C, Coleman K, Cox P, Fallon P, Jenkinson D, Powlson D (2005) Global climate changes and soil carbon stocks; predictions from two contrasting models for the turnover of organic carbon in soils. *Glob Change Biol* 11(1):154–166. <https://doi.org/10.1111/j.1365-2486.2004.00885.x>
- Juma NG, Paul EA (1981) Use of tracer and computer simulation techniques to assess mineralisation and immobilisation of soil nitrogen. In: Frissel MJ, van Veen JA (eds) *Simulation of nitrogen behaviour of soil-plant systems*. Pudoc, Wageningen, pp 145–154
- Kalbitz K, Solinger S, Park JH, Michalzik B, Matzner E (2000) Controls on the dynamics of organic matter in soils: a review. *Soil Sci* 165(4):277–304. <https://doi.org/10.1097/00010694-200004000-00001>
- Keesstra SD, Geissen V, Mosse K, Piirainen S, Scudiero E, Leistra M, Van Schaik L (2012) Soil as a filter for groundwater quality. *Curr Opin Environ Sustain* 4(5):507–516. <https://doi.org/10.1016/j.cosust.2012.10.007>
- Komorov A, Chertov O, Bykhovets S, Shaw C, Nadporozhskaya M, Frolov P, Shashkov M, Shanin V, Grabarnik P, Pripulina I, Zubkov E (2016) Romul\_Hum model of soil organic matter formation coupled with soil biota activity, I, Problem formulation, model description, and testing. *Ecol Model* 345:314–124. <https://doi.org/10.1016/j.ecolmodel.2016.08.007>
- Kononova MM (1966) *Soil organic matter: its nature, its role in soil formation and in soil fertility*, 2nd edn. Pergamon Press, Oxford
- Kolenbrander GJ (1969) De bepaling van de waarde van verschillende soorten organische stof ten aanzien van hun effect op het humusgehalte bij bouwland. Inst. Bodemvrucht, Haren
- Kortleven H (1963) Quantitative aspects of humus accumulation and decomposition. Versl Landbk Onderz, vol. 69.1. Pudoc, Wageningen
- Kutsch WL, Aubinet M, Buchmann N, Smith P, Osborne B, Eugster W, Wattenbach M, Schrumpp M, Schulze ED, Tomelleri E, Ceschia E, Bernhofer C, Beziat P, Carrara A, Di TP, Grunwald T, Jones M,

- Magliulo V, Marloie O, Moureaux C, Olioso A, Sanz AJ, Saunders M, Søgaard H, Ziegler W (2010) The net biome production of full crop rotations in Europe. *Agric Ecosyst Environ* 139(3):336–345. <https://doi.org/10.1016/j.agee.2010.07.016>
- Kwiatkowska J, Provenzano MR, Senesi N (2008) Long-term effects of brown coal-based amendment on the properties of soil humic acids. *Geoderma* 148(2):200–205. <https://doi.org/10.1016/j.geoderma.2008.10.001>
- Lal R (2001) World cropland soils as a source or sink for atmospheric carbon. *Adv Agron* 71:145–191. [https://doi.org/10.1016/S0065-2113\(01\)71014-0](https://doi.org/10.1016/S0065-2113(01)71014-0)
- Lal R (2004a) Soil carbon sequestration impacts on global climate change and food security. *Science* 304(5677):1623–1627. <https://doi.org/10.1126/science.1097396>
- Lal R (2004b) Agricultural activities and the global carbon cycle. *Nutr Cycl Agroecosys* 70(2):103–116. <https://doi.org/10.1023/B:FRES.0000048480.24274.0f>
- Lal R, Griffin M, Apt J, Grave L, Morgan MG (2004) Managing soil carbon. *Science* 304(5669):393. <https://doi.org/10.1126/science.1093079>
- Leenheer J. (2016) The unique structural chemistry of humic substances. 01-01 Proc 18th Int. IHSS Conf., Kanazawa, Japan
- Lehmann J, Kleber M (2015) The contentious nature of soil organic matter. *Nature* 528(7580):60–68. <https://doi.org/10.1038/nature16069>
- Leithold G, Hulsbergen KJ, Brock C (2015) Organic matter returns to soils must be higher under organic compared to conventional farming. *J Plant Nutr Soil Sci* 178(1):4–12. <https://doi.org/10.1002/jpln.201400133>
- Leszczyńska D, Kwiatkowska-Malina J (2011) Effect of organic matter from various sources on yield and quality of plants on soils contaminated with heavy metals. *Ecological Chem Eng* 18(4):501–507
- Lorenz K, Lal R (2012) Cropland soil carbon dynamics. Recarbonization of the biosphere. pp 303–346. [https://doi.org/10.1007/978-94-007-4159-1\\_14](https://doi.org/10.1007/978-94-007-4159-1_14)
- Mader P, Fliessbach A, Dubois D, Gunst L, Fried P, Niggli U (2002) Soil fertility and biodiversity in organic farming. *Science* 296(5573):1694–1697. <https://doi.org/10.1126/science.1071148>
- Manzoni S, Trofymow JA, Jackson RB, Porporato A (2010) Stoichiometric controls on carbon, nitrogen, and phosphorus dynamics in decomposing litter. *Ecol Monogr* 80(1):89–106. <https://doi.org/10.1890/09-0179.1>
- Minasny B, Malone BP, McBratney AB, Angers DA, Arrouays D, Chambers A, Chaplot V, Chen Z-S, Cheng K, Das BS, Field DJ, Gimona A, Hedley CB, Hong SY, Mandal B, Marchant BP, Martin M, McConkey BG, Mulder VL, O'Rourke S, Richer-de-Forges AC, Odeh I, Padarian J, Paustian K, Pan G, Poggio L, Savin I, Stolbovov V, Stockmann U, Sulaeman Y, Tsui C-C, Vågen T-G, van Wesemael B, Winowiecki L (2017) Soil carbon 4 per mille. *Geoderma* 292:59–86. <https://doi.org/10.1016/j.geoderma.2017.01.002>
- Molina JAE, Clapp CE, Shaffer MJ, Chichester FW, Larson WE (1983) NCSOIL, a model of nitrogen and carbon transformations in soil: description, calibration, and behavior. *Soil Sci Soc Am J* 47(1):85–91. <https://doi.org/10.2136/sssaj1983.03615995004700010017x>
- Muñoz C, Paulino L, Monreal C, Erick Zagal E (2010) Greenhouse gas (CO<sub>2</sub> and N<sub>2</sub>O) emissions from soils: a review. *Chil J Agr Res* 70(3):485–497
- Nebbioso A, Drosos M, Zuhleke S, Spiteller M, Piccolo A (2016) Direct humeome extraction from two German soils and molecular characterization by Electropray-Orbitrap-Mass Spectrometry (ESI-Orbitrap-MS). 01-08 Proc 18th International IHSS Conf, Kanazawa, Japan
- Nortcliff S (2002) Standardisation of soil quality attributes. *Agric Ecosyst Environ* 88(2):161–168. [https://doi.org/10.1016/S0167-8809\(01\)00253-5](https://doi.org/10.1016/S0167-8809(01)00253-5)
- Novotny EH, Branco de Freitas M, Claudia M, Carvalho MT, Madari BE (2015) Biochar: pyrogenic carbon for agricultural use—a critical review. *Revista Brasileira de Ciencia do Solo* 39(2):321–344. <https://doi.org/10.1590/01000683rbc20140818>
- Oertel C, Matschullat J, Zurba K, Zimmermann F, Erasmí S (2016) Greenhouse gas emissions from soils—a review. *Chemie der Erde - Geochemistry* 76(3):327–352. <https://doi.org/10.1016/j.chemer.2016.04.002>
- Ouyang L, Yu L, Zhong R (2014) Effects of amendment of different biochars on soil carbon mineralization and sequestration. *Soil Res* 52(1):46–54. <https://doi.org/10.1071/SR13186>
- Ouyang W, Gao X, Wei P, Gao B, Lin C, Hao F (2017) A review of diffuse modeling and associated implications for watershed management in China. *J Soils Sediments* 17(6):1527–1536. <https://doi.org/10.1007/s11368-017-1688-2>
- Parnas H (1975) Model for decomposition of organic material by microorganisms. *Soil Biol Biochem* 7(2):161–169. [https://doi.org/10.1016/0038-0717\(75\)90014-0](https://doi.org/10.1016/0038-0717(75)90014-0)
- Patron WJ, McKeown B, Kirchner V, Ojima DS (1992) CENTURY users manual. Colorado State University, NRE L Publication, Fort Collins
- Penning de Vries FWT (1982) Systems analysis and models of crop growth. In: Penning de Vries FWT, van Laar HH (eds) Simulation of plant growth and crop production. Simulation monographs. Pudoc, Wageningen, pp 9–19
- Rawls WJ, Pachepsky YA, Ritchie JC, Sobecki TM, Bloodworth H (2003) Effect of organic carbon on soil water retention. *Geoderma* 116(1-2):61–76. [https://doi.org/10.1016/S0016-7061\(03\)00094-6](https://doi.org/10.1016/S0016-7061(03)00094-6)
- Reeves DW (1997) The role of soil organic matter in maintaining soil quality in continuous cropping systems. *Soil Till Res* 43(1-2):131–167. [https://doi.org/10.1016/S0167-1987\(97\)00038-X](https://doi.org/10.1016/S0167-1987(97)00038-X)
- Rumpel C, Kogel-Knabner I, Huttel RF (1999) Organic matter composition and degree of humification in lignite-rich mine soils under a chronosequence of pine. *Plant Soil* 213(1/2):161–168. <https://doi.org/10.1023/A:1004454826537>
- Sauerbeck DR (2001) CO<sub>2</sub> emissions and C sequestration by agriculture—perspectives and limitations. *Nutr Cycl Agroecosyst* 60(1/3):253–266. <https://doi.org/10.1023/A:1012617516477>
- Sauerbeck DR, Gonzalez MA (1977) Field decomposition of carbon-14-labelled plant residues in various soils of the Federal Republic of Germany and Costa Rica. *Soil Organic Matter Studies. Proceedings of a symposium organized by IAEA, FAO and Agrochimica, Braunschweig, vol. I, pp 159–170*
- Schmidt MW, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, Kleber M, Kogel-Knabner I, Lehmann J, Manning DAC, Nannipieri P, Rasse DP, Weiner S, Trumbore SE (2011) Persistence of soil organic matter as an ecosystem property. *Nature* 478(7367):49–56. <https://doi.org/10.1038/nature10386>
- Schnitzer M, McArthur DFE, Schulten H-R, Kozak LM, Huang PM (2006) Long-term cultivation effects on the quantity and quality of organic matter in selected Canadian prairie soils. *Geoderma* 130(1-2):141–156. <https://doi.org/10.1016/j.geoderma.2005.01.021>
- Schrumpf M, Schulze ED, Kaiser K, Schumacher J (2011) How accurately can soil organic carbon stocks and stock changes be quantified by soil inventories? *Biogeosciences* 8(5):1193–1212. <https://doi.org/10.5194/bg-8-1193-2011>
- Scotti R, Bonanomi G, Scelza R, Zoina A, Rao MA (2015) Organic amendments as sustainable tool to recovery fertility in intensive agricultural systems. *J Soil Sci Plant Nutr* 15(2):333–352
- Shahbaz M, Kuzyakov Y, Heitkamp F (2017) Decrease of soil organic matter stabilization with increasing inputs: mechanisms and controls. *Geoderma* 304:76–82. <https://doi.org/10.1016/j.geoderma.2016.05.019>
- Shibu ME, Leffelaar PA, Van Keulen H, Aggarwal PK (2006) Quantitative description of soil organic matter dynamics—a review of approaches with reference to rice-based cropping systems.

- Geoderma 137(1-2):1–18. <https://doi.org/10.1016/j.geoderma.2006.08.008>
- Seligman NG, Van Keulen H (1981) PAPERAN: a simulation model of annual pasture production limited by rainfall and nitrogen. In: Frissel MJ, van Veen JA (eds) Simulation of nitrogen behavior of soil plant systems. Pudoc, Wageningen, pp 192–220
- Sequi P, De Nobili M, Leita M, Cercignani G (1986) A new index of humification. *Agrochimica* 30:175–179
- Six J, Jastrow JD (2002) Organic matter turnover. In: Lal R (ed) Encyclopedia of soil science. Marcel Dekker, New York
- Smith P (2012) Soils and climate change. *Curr Opin Environ Sustain* 4(5):539–544. <https://doi.org/10.1016/j.cosust.2012.06.005>
- Sohi SP, Krull E, Lopez-Capel E, Bol R (2010) A review of biochar and its use and function in soil. Chapter 2. *Adv Agron* 105:47–82. [https://doi.org/10.1016/S0065-2113\(10\)05002-9](https://doi.org/10.1016/S0065-2113(10)05002-9)
- Stevenson FJ (1994) Humus chemistry: genesis, composition, reactions. 2nd edn. Wiley, New York
- Strosser E (2010) Methods for determination of labile soil organic matter: an overview. *J Agrobiol* 27(2):49–60
- Sutton R, Sposito G (2005) Molecular structure in soil humic substances: the new view. *Environ Sci Technol* 39(23):9009–9015. <https://doi.org/10.1021/es050778q>
- Usman K, Khan S, Ghulam S, Khan MU, Khan N, Khan MA, Khan Khalil S (2012) Sewage sludge: an important biological resource for sustainable agriculture and its environmental implications. *Am J Plant Sci* 3(12):1708–1721. <https://doi.org/10.4236/ajps.2012.312209>
- Van Ittersum MK, Leffelaar PA, Van Keulen H, Kropff MJ, Bastiaans L, Goudriaan J (2002) Developments in modelling crop growth, cropping systems and production systems in the Wageningen school. *Neth J Agric Sci* 50:239–247
- Van Keulen H (2001) (Tropical) soil organic matter modelling: problems and prospects. *Nutr Cycl Agroecosyst* 61(1/2):33–39. <https://doi.org/10.1023/A:1013372318868>
- Van Veen JA, Frissel MJ (1981) Simulation model of the behavior of N in soil. In: Frissel MJ, Van Veen JA (eds) Simulation of nitrogen behavior of soil plant systems. Pudoc, Wageningen, pp 126–144
- Van Veen J, Paul EA (1981) Organic carbon dynamics in grassland soils: 1. Background information and computer simulation. *Can J Soil Sci* 61(2):185–201. <https://doi.org/10.4141/cjss81-024>
- Verberne ELJ, Hassink J, De Willigen P, Groot JJR, van Veen JA (1990) Modelling organic matter dynamics in different soils. *Neth J Agric Sci* 38:221–238
- Wadman WP, de Hann S (1997) Decomposition of organic matter from 36 soils in long-term pot experiment. *Plant Soil* 189(2):289–301. <https://doi.org/10.1023/A:1004228127741>
- Watt M, Kirkegaard JA, Passioura JB (2006) Rhizosphere biology and crop productivity—a review. *Aust J Soil Res* 44(4):299–317. <https://doi.org/10.1071/SR05142>
- Yang HS, Janssen BH (2000) A mono-component model of carbon mineralization with a dynamic rate constant. *Eur J Soil Sci* 51(3):517–529. <https://doi.org/10.1046/j.1365-2389.2000.00319.x>
- Yigini Y, Panagos P (2016) Assessment of soil organic carbon stocks under future climate and land cover changes in Europe. *Sci Total Environ* 557–558:838–850. <https://doi.org/10.1016/j.scitotenv.2016.03.085>
- Zech W, Senesi N, Guggenberger G, Kaiser K, Lehmann J, Miano TM, Miltner A, Schroth G (1997) Factors controlling humification and mineralization of soil organic matter in the tropics. *Geoderma* 79(1-4):117–161. [https://doi.org/10.1016/S0016-7061\(97\)00040-2](https://doi.org/10.1016/S0016-7061(97)00040-2)