Functions, services and value of soil organic matter for human societies and the environment: a historical perspective

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Abstract: Soil organic matter (SOM) contributes significantly to the chemical, physical and biological ecosystem functions of soil. It influences on plant growth, thus contributing to agricultural production, and performs environmentally valuable services such as carbon sequestration, regulation of the water cycle and detoxification of pollutants. Identification of the functions and services provided by SOM has a long and tumultuous history of scientific discoveries and struggles against false assumptions. This work reports the major steps of this history, with emphasis on two services secured by SOM: (1) the role of SOM in plant production and its connection to soil fertility and thence to the sustainability of cropping and farming systems; and (2) the recognition and assessment of the contribution of SOM to climate-change regulation. Finally, the work explores how SOM, as a multifunctional resource, may be allocated an economic value as a way of promoting its conservation.

It remains difficult to decide whether soil resources should be seen as renewable. However, archaeologists have identified examples of human societies that have been brought to the limit of sustainability by soil depletion, even resulting in some cases in the decline and fall of their civilization (Hyams 1976; Olson 1981). Today, the role of soil organic matter in controlling the capacity of soil resources to deliver agricultural and environmental services and sustain human societies at both local (e.g. fertility maintenance) and global (e.g. mitigation of atmospheric carbon emissions) scales is well established (Tiessen *et al.* 1994; Syers & Craswell 1995; Wolf & Snyder 2003). Soil organic matter (SOM) contributes to a range of functions that can be connected to goods and services at the ecosystem level (Table 1). Scientific recognition of the relationship between SOM, the sustainability of human activities and the state of the environment, and its implications for farming practices and land-use management options, have fluctuated over time. This is in part due to continuing difficulty in adequately distinguishing and defining SOM functions and quantifying their values in terms of the environmental services that they provide, and in part to erroneous attributions of the

Table 1. *Main functions, 'goods' and 'services' of soil organic matter at the ecosystem level*

Functions	Ecosystem goods and services
Nutrient reserves for plant and soil biota (decomposition, mineralization processes)	Nutrient storage and availability; chemical fertility
Energy reserve for soil biota; micro- and macro-habitat building	Regulation of biological populations, including diseases and pests; biodiversity
Aggregate formation and stabilization	Regulation of water flow and storage, and regulation of soil and sediment movement
Decomposition, sorption; elemental transformation	Detoxification of chemical and biological pollutants (including water purification)
Sink/source of greenhouse gases	Regulation of atmospheric composition and climate

FROM: FROSSARD, E., BLUM, W. E. H. & WARKENTIN, B. P. (eds) 2006. *Function of Soils for Human Societies and the Environment.* Geological Society, London, Special Publications, **266**, 9–22.

agro-ecological functions of SOM that have been made at various times.

The objective of this work is not to give a detailed review of the present knowledge of the functions and services provided by SOM to human societies and the environment, but to present a brief history of the construction of concepts and tools that lead to the perception of the interconnection between SOM, soil fertility and ecosystem sustainability. We also briefly address ways in which society has begun to attribute both ecological and economic value to SOM. The focus of this paper is on two broad functions of SOM: the first is productive and relates to ecosystem fertility and farming sustainability; the second is environmental and deals with the control of the greenhouse effect, climate change and soil carbon (C) sequestration.

Agronomic functions of soil organic matter and their connection to cropping and farming sustainability: a complex and tumultuous history

From antiquity to the eighteenth century

Concepts of plant nutrition varied greatly during antiquity (Browne 1944). Among the Greek philosophers in the period from 640 to 435 BC, sources of plant material were: water for Thales of Miletus, *c.* 625 to *c.* 546 BC; air for Anaxinemes (*c.* 585 to *c.* 525 BC); fire for Heraclitus (*c.* 535 to *c.* 475 BC); and for Empedocles all four of the basic elements (earth, water, air and fire). Aristotle (384–322 BC) used these precedent theories to establish the general 'Four Elements Theory', whereby the union of the four elements in the soil enables minute particles to sustain plant nutrition. As a consequence, all plant material was thought to originate from soil. According to Aristotle soil fertility – like anything in nature – would also be driven by the 'four qualities' – warmth, coldness, humidity and dryness. Plants were also assumed to feed on organic material of related nature: for instance, olive stones were fed to olive trees, and vine shoots to vines, to sustain plant production. Such beliefs and Aristotle's theory were still influential during the Middle Ages. Palissy (1510–1589), whose theory of 'salts' was published in 1580 (in Palissy 1880) is generally considered by historians of soil science to be a major forerunner of the mineral theory later established by Liebig (1803–1873) (Liebig 1840); however, since Palissy's definition of 'salt' is not strictly mineral, this opinion is questionable (Feller *et al.* 2001, 2003). In the seventeenth century, Van Helmont (1577–1644), among others, took up Palissy's ideas about the role of soil as a simple source of water and mineral nutrients for the plant (Boulaine 1989). In 1699, Woodward (1665–1728) showed that something from the earth, other than water, was important to plant growth.

During the eighteenth century, 'humus' was often understood to be synonymous with soil, and many theories and agricultural practices (e.g. soil tillage; Tull 1733) about plant nutrition were based on the belief that plants relied directly on humus for their own carbon supply.

SOM as a possible source for plant carbon nutrition (1800–1900). By the end of the eighteenth century, Hassenfratz (1755–1827) still asserted, but without referring to experimental facts, that a fraction of humus in the form of soluble carbon was directly assimilated by plants (carbon heterotrophy) and was the almost unique source for plant carbon nutrition (Feller *et al.*, 2001). But during the same period several authors – all cited in Bourde (1967), for example, Priestley (1733–1764) (Priestley 1777), Ingen-Housz (1730–1799) (Ingen-Housz 1780), Senebier (1742–1809) (Senebier 1782) and de Saussure (1740–1799) (de Saussure 1804) – partially refutated these theories by demonstrating experimentally both the gaseous origin of carbon and the role of light during photosynthesis. Nonetheless, de Saussure still considered that a small part of plant material could derive from soluble humus. Contradictory debates arose on the subject, but many agricultural scientists shared an intermediary point of view and assigned functions in plant nutrition to both SOM and air. This was in particular the case for the famous German agronomist Albrecht Daniel Thaër (1752–1828), known for the 'theory of humus' developed in his seminal book *Principles of Rational Agriculture* (Thaër 1809).

Thaër's Principles. Thaër's *Principles* contains some unverified theoretical concepts of plant nutrition that served as a basis for the first rational and systematic approach to fertilization within the context of sustainable cropping practices (de Wit 1974; Feller *et al.* 2003). Thaër's theory of humus (1809) integrated an analysis of the management of soil fertility and the concept of sustainability that deserves particular attention.

Thaër's book was released in the midst of a period of controversy about whether the soil or the atmosphere was the actual source of carbon used by plants. Thaër did not deny that atmospheric CO_2 could be a carbon source for the plant, but since this compartment seemed unlimited, he considered soil humus and its management as the main limiting factor of plant carbon nutrition. According to Thaër: (1) the majority of plant dry-matter derives from the 'soil nutritive juices' contained in the fraction of soil humus that is soluble in hot water; and (2) plant demand for 'juices' is selective and varies with the species cultivated. Therefore management of soil fertility must be based on the management of the soil humic balance as well as on that of the crop succession.

Although incorrect, these theoretical assertions encompassed the whole soil–plant system and were used to support the first quantified, complex but complete system of analysis for the diagnosis and prediction of fertility (Feller *et al.* 2003). This is certainly the first example of real concern about farming sustainability, and what is more, it is based on organic practices. Thaër's analysis also included an economic approach (see p. 18).

Conceptually, Thaër's approach to fertility encompassed the plant–soil system as well as cropping patterns and rotations. In so doing he introduced and discussed modern agricultural issues, such as the identification of soil-quality indicators, systematic analysis and the agroeconomic sustainability of farming systems. His work seriously influenced the thinking of his peers during the first half of the nineteenth century. If Thaër had focused on mineral rather than organic budgets, he would probably have been regarded as the founder of Western scientific agriculture.

From the 'mineral theory' to the new concept of bioavailability and the indirect role of SOM in mineral nutrition. Although Liebig took many of his ideas from the work of Sprengel (1787–1858) (Sprengel 1838, *in* van der Ploeg *et al.* 1999), his authoritative text *Die organische Chemie in ihrer Anwendung auf Agrikultur und Physiologie* (1840) is often considered as the first demonstration, based on scientific experiments, of the origin of plant dry-matter from mineral compounds. Carbon was described as being derived from carbon dioxide; hydrogen from water; and other nutrients from soluble salts in soil and water. Since Liebig's synthesis accounted rather satisfactorily for the fertilizing effect of mineral inputs, it provided the basis for modern agricultural sciences. Liebig promoted the use of mineral fertilizers to compensate for soil mineral depletion, and his work paved the way for recommendations for the massive use of chemical fertilizers in cropping systems, and the abandonment of organic or organomineral fertilization. Nonetheless, Liebig, as '*one of the last* "complete" *men among the Great Europeans*' (Hyams 1976), was himself an advocate of mixed fertilization. In the sixth volume of his exhaustive *Cours d'Agriculture*, Gasparin (1783–1862) (Gasparin 1860) took a similarly moderate position: he included organic and chemical fertilizers in the same category, but was already emphasizing the low economic cost of organic fertilizers produced on the farm. In fact, the limited references to chemical fertilizers in Gasparin's textbook are certainly due to the limited production and use of inorganic fertilizers before the 1880s (Boulaine 1989; Smil 1999).

Finally, direct but very limited absorption of some organic compounds by plant roots was to be demonstrated in the early twentieth century (Acton 1899; Mazé 1899, 1904, 1911; Laurent 1904; Cailletet 1911; Knudson 1916, all cited by Waksman 1938). Today, the importance of humic substances for enhancing absorption of mineral, organic or organomineral phytohormones is well recognized (Chen, 1996; Chen *et al.* 2004).

From agronomy to ecology

The mineralist approach to the management of soil fertility reached its apogee in the thirty-year period following the Second World War, with the establishment of high-input, subsidized agriculture in Europe and North America, and the huge fertilizer-driven increases in the production of Green Revolution cultivars of rice, wheat and maize in South and South East Asia and parts of Latin America (Pinstrup-Anderson & Hazell 1985). As a result, interest within the conventional agricultural research community in managing SOM as a source of fertility declined even further. In contrast, the same time period, however, saw the rise of a number of other scientific initiatives that resulted, in the last two decades of the century, in renewed and scientifically based interest in managing SOM under the rubric of 'sustainable agriculture'. These approaches can be seen as being derived substantially from two convergent sources: firstly, developments in ecosystem science, including improved scientific capacity for the study of SOM and associated aspects of nutrient cycling; and, secondly, concerns about environmental degradation and the loss of ecosystem services, and the expression of these concerns in the rise of the organic farming movement.

The 'healthy' function of SOM and the organic farming movement. The concerns about the impacts of high-input agriculture expressed by the formal scientific sector were probably less influential in triggering of new interests in the management of SOM as a component of soil fertility than those derived from the rise of 'alternative' farming practices under the rubric of 'organic agriculture'. Predating the conceptual debate about the substitutability of organic amendments by chemical fertilizers (Smil 1999; Rigby & Caceres 2001), societal criticisms concerning the sustainability of intensive farming arose as early as the 1930s, leading to the formulation by Balfour (1944) of a hypothesis of the link between the decline in soil fertility, the quality of the human diet and the state of human health. Concerns about the loss of biological function and decline in fertility in cropped soils that are managed without returning organic matter to the soil, date back to ancient times, but the lack of sound principles of soil ecology diminished their impact on scientific thinking. Steiner's lectures (1924) provided the foundation for biodynamic agriculture. The scientific basis of Steiner's lectures and of the publications of his followers (e.g. Pfeiffer 1938) was poor, as they referred to both holistic and cosmogonic concepts (i.e. interrelations between the stars, soil and geochemical elements, plants, animals and humans) as the basis for a new kind of agriculture that excluded the use of any chemical input. The most influential – and at least rational – publications on modern organic farming are those from Howard, Balfour and Rodale (Howard 1940; Balfour 1944; Rodale 1945; Howard 1952); for a more detailed review of the history of organic farming, see Scofield (1986) and Lotter (2003). The main objective that they shared was to improve soil, plant, animal and human health by the biological management of soil fertility. Two fundamental aspects of the organic farming philosophy put SOM at the heart of cropping sustainability: the holistic paradigm and the Law of Return.

The holistic paradigm. In *The Living Soil*, Balfour (1944) presented the quintessence of the philosophy of organic farming. Her leading hypothesis was that the reason for the obvious – according to her criteria – decline in the health of the human race was the decrease in plant health, itself a consequence of the decline in the health of the soil. The philosophy of organic farming is fundamentally holistic and perceives

> all life, all creation as being inextricably interrelated, such that something done or not done to one member, part or facet will have an effect on everything else. (Merrill, 1983)

This is best illustrated by the biotic pyramid of Albrecht (1975, cited *in* Merrill 1983).

This pyramid is made of several layers, with the soil as the basement and humans at the top of the pyramid. Within this scheme, any degradation of soil quality can threaten civilization and even humankind itself – hence the need for careful soil husbandry.

The Law of Return. Another principle of organic farming is the Law of Return. It stems from the concept of the 'Living substances cycle', which originated in antiquity and reappeared in treatises on agriculture in the sixteenth and seventeenth centuries. The breaking of this principle is one of the factors suggested in several historical records where collapses of civilizations have been attributed to failures of their agriculture, and it still underpins present critical issues in urban waste recycling (Magid *et al.* 2001). According to this principle, life can be maintained only if living beings, or at least the residues of their activity and body decomposition, are cycled at each step of the biotic pyramid. A crucial process is thus the establishment of organic flows to the soil to maintain its fertility. Since this return is SOM-mediated, Balfour (1944), and above all Rusch (1972), adopted a sceptical position towards what they termed Liebig's '*rather naïve theory*', and developed a partly rigorous (Balfour and Howard), partly ideological (Rusch) analysis of the agro-ecological role of SOM. Howard's opinion, as expressed in his *The Soil and Health* (1952) matches Balfour's holism. His more precise causal interpretation of the relation between soil, plant, animal and human health is anchored in the idea of the cycling of proteins among living beings, and their quality of protein. Even if his opinions were partly ideological, Howard (1940, 1952) did publish rigorous and famous technical handbooks for the production of compost, which he termed 'manufactured humus'.

For the past 10 years, in scientific community, there has been a renewed interest in holistic approaches to soil management, as evidenced by the proliferation of scientific meetings, research programmes (and, of course, the consequent publications) on the topics of 'soil health', 'soil quality' indicators and 'sustainable soil management'. SOM (total or in compartments) and soil biota are invariably key parameters of these initiatives (Lavelle & Spain 2001; Doran 2002).

Towards ecological agriculture. Setting aside the ideological elements, there is clearly a degree of convergence between some of the holistic principles of organic agriculture and those of ecosystem science. This convergence has been embraced in the developing concepts of 'sustainable' or 'ecological' agriculture. The term 'sustainable development' came to global attention with the publication of the report of the World Commission on Environment and Development (WCED 1987), where it was defined as '*development that meets the need of present generations without compromising the ability of future generations to meet their own needs*'. This obvious congruence with the environmental concerns about the impact of intensive high-input agriculture, coupled with the failure to achieve persistent and consistent results in many parts of the world, notably Africa, stimulated a substantial effort to find sustainable means of agricultural production (Conway & Barbier 1990). This focus naturally fell upon the use of renewable natural resources; in the case of soil-fertility management this resulted in fresh attention being given to the management of organic matter and biological processes (Scholes *et al.* 1994).

One of the key features of sustainable soil practice is the return to managing soil fertility through the combination of organic matter (crop residue, compost or manure) and mineral nutrient inputs (Pieri 1992). This rediscovery of the benefits of the ancient concept of integrated nutrient management became the mainstay of soil-fertility management at the turn of the twentieth century (Mokwunye & Hammond 1992; Palm *et al.* 1997), and maintenance and/or improvement of SOM status is central to the philosophy. Management of organic inputs has been able to draw on the knowledge gained from ecological studies of decomposition processes, nutrient cycles and nutrient balances (Myers *et al.* 1994; Cadisch & Giller 1997; Palm *et al.* 2001). Similarly, the management of SOM has been enhanced by the application of the knowledge embedded in different simulation models, with a particular focus on manipulating the labile pools, while seeking to maintain or build up the stable SOM fractions (Vanlauwe *et al.* 1994). The major scientific challenge remains how to extend the ecological principles beyond the manipulation of the plant component (with the consequent indirect influence on the soil biota, decomposition processes and SOM dynamics) to more direct manipulation of the soil biota (Swift, 1998). Successes obtained with the dinitrogen (N_2) fixing bacteria (Giller 2001) have, however, still to be matched in other groups of soil biota.

Since Odum's strategy of ecosystem development (1969), general conceptual advances have stressed the aptitude of ecosystems – based on their internal organization – to escape the constraints of the abiotic environment by building biotic buffers or even modifying abiotic factors (Perry *et al.* 1989). In terrestrial ecology, SOM has been recognized as a pivotal factor buffering climate and soil constraints and establishing close links between plants and soils from the perspective of ecosystem rehabilitation (Perry *et al.* 1989; Aronson & Le Floc'h 1996). The contradiction that appeared subsequently – between the role of SOM as a source of nutrients requiring its decomposition and its structural role in improving soil physical and chemical properties and stabilizing the plant–soil interactions – has been underlined by de Ridder & van Keulen (1990). In fact, recent applications of the thermodynamic theories of open systems kept far from their equilibrium, such as a soil ecosystem, may have at least partially solved this contradiction (Odum *et al.* 2000). They suggest that soil structure and organization can be largely controlled by soil biota at the cost of energy – mostly carbon-mediated – dissipation, thus implying SOM recycling (Perry *et al.* 1989).

The treatment of SOM as a dynamic, biologically regulated pool of carbon and nutrients in science-based sustainable agriculture converges with Balfour's definition of soil fertility in organic agriculture as '*the capacity of soil to receive, store and transmit energy*' (Balfour 1976, in Merrill 1983).

Increased promotion or adoption worldwide of precision agriculture, agroforestry (Steppler & Nair 1987; Ewel 1999), and of composting, mulching, direct sowing, reduced tillage and cover cropping (CIRAD 1999; Erenstein 2003) testifies to the renewed recognition of the scientific value of integrated SOM management for the development of sustainable cropping patterns. Similarly the incorporation of ecological concepts into modern agriculture, although slow, represents a return to principles that were generally widespread before the mineralist era and which were derived empirically from observation of nature, many of which have been retained in traditional indigenous knowledge in many parts of the world (Altieri 2002; Jackson 2002; Tilman *et al.* 2002). This progress has been documented recently in a book (McNeely & Scherr 2002) which celebrates the achievements of what they term 'Ecoagriculture'.

An environmental function of SOM: control of the greenhouse effect and carbon sequestration

Beyond its role in nutrient cycles, SOM has also come to be valued for its influence on a wide range of so-called ecosystem services. These include structure-related features such as water storage and availability and resistance to soil erosion, as well as the energy contributed to supporting the biomass and diversity of the soil biota and their actions as biological control agents and regulators of soil and water pollution (Swift *et al.* 2004). Nonetheless, these benefits depend on balance. High levels of SOM can also create negative effects such as excessive nitrate production, and application of large amounts of organic matter can result in the build-up of pests (Chikowo *et al.* 2004).

In recent years, increasing attention has been given to the potential of SOM for carbon sequestration. Concerns about increasing atmospheric greenhouse gas concentrations (GHG, mainly CO_2, CH_4 and N_2O) and global warming and climate change, have raised questions about the role of soils as sources or sinks of carbon (Houghton 2003). The terms 'sequestration' and 'C sequestration' were proposed to define the aptitude of terrestrial ecosystems to act as sinks for these GHG. Key aspects of the history of the appearance and significance of the term 'carbon sequestration' and of methods to estimate it in soil at different scales in time and space as well as those procedures used to measure CO_2 fluxes in the soil–plant system, are presented briefly below.

Appearance of the terms 'carbon sequestration' and 'soil carbon sequestration'

A search of the ISI-Web of Science database for the 1945–2005 time period suggests that the first occurrence of the linked terms 'soil' and 'carbon' and 'sequestration' dates from only 1991, but the number of references has increased rapidly over the past 15 years (Bernoux *et al.* 2006) (Table 2). The concept of soil C sequestration is thus relatively new.

Most definitions of C sequestration, whether soil specific or not, refer simply to CO_2 removal from the atmosphere and storage in an organic form in the soil or plant compartments. But methane (CH_4) and nitrous oxide (N_2O) are also involved in exchanges between the soil–plant system and the atmosphere. The Kyoto Protocol includes an inventory of all sources and sinks of these gases. Net GHG emission calculations of the signatories of the United Nations Framework Convention on Climate Change (UNFCCC) are expressed for all the gases in equivalents of CO_2 after application of a conversion factor, the global warming potential (GWP) of each gas. Current conventions yield a 100-year-GWP value of 23 for CH_4 and 296 for N_2O. A recent review by Six

Table 2. *Number of references indexed in the ISI-Web of Science (1945–2005) returned by combining the queries (1) 'soil' AND 'carbon', and (2) 'soil' AND 'carbon' AND 'sequestration', in the 'topics' and 'title' (between brackets, Query 2 only) fields. Updated from Bernoux* et al. *(2006)*

Period	Number of references returned by query			Query 2:Query 1 ratio (‰)
	1 = 'soil' AND 'carbon'	2 = 'soil' AND 'carbon' AND 'sequestration'		
1945–1990	719	0		0
1991	643	1*		1.6
1992	694	5	(1†)	7.2
1993	816	14	(1)	17.2
1994	908	7		7.7
1995	985	21	(1)	21.3
1996	1220	24		19.7
1997	1398	36	(2)	25.7
1998	1520	47	(3)	30.9
1999	1568	42	(3)	26.8
2000	1618	78	(8)	48.2
2001	1727	107	(14)	67.5
2002	1850	153	(15)	82.7
2003	2136	217	(33)	101.6
2004	2142	174	(17)	81.2
2005	2611	255	(26)	97.6
Total (1940–2005)	21555	1181	(126)	54.8

* Thornley *et al.* (1991); † Dewar and Cannell (1992).

et al. (2002) illustrates the importance of those considerations. The authors found that: (1) in both tropical and temperate soils, C levels increased in no-tillage (NT) systems as compared to those under conventional tillage (CT); but (2), in temperate soils average N_2O emissions increased substantially under NT as compared to CT; and (3) the increase in N_2O emissions (when expressed on a C–CO_2 equivalent basis) lead to a negative total GWP, even if positive C storage was observed in the soil. Even N fertilization in an organic form is an N_2O emission hazard (Flessa *et al.* 2002; Giller *et al.* 2002; Millar *et al.* 2004).

From these considerations, it appears clear that a concept of 'soil carbon sequestration' must not be restricted to a mere quantification of C storage or CO_2 balance. All GHG fluxes must be computed at the plot level in C–CO_2 or CO_2 equivalent, incorporating as many emission sources and sinks as possible across the entire soil–plant system. Therefore, Bernoux *et al.* (2006) propose a new definition for C sequestration, applied to the soil or soil–plant-system:

> 'Soil carbon sequestration' or 'Soil–plant carbon sequestration', for a specific agro-ecosystem, in comparison with a reference one, should be considered as the result, for a given period of time and portion of space, of the net balance of all GHGs, expressed in C–CO_2 equivalent or CO_2 equivalent, computing all emissions sources at the soil–plant–atmosphere interface.

The confusion (as is often the case) between the notion of 'SOC (SOC, soil organic carbon) storage' (C stored in the soil whatever its origin) and 'soil C sequestration' (GHGs, expressed in equivalent C–CO_2 stored in the soil and originating from the atmosphere) can thus be avoided.

The first measurements of soil CO_2 concentration and fluxes

The discovery of carbon dioxide is attributed to Joseph Black (1728–1799), who published his thesis in 1754. Black named it 'fixed air', for it was emitted during heating and decomposition of calcium or magnesium carbonates.

The first in situ *and* in vitro *measurements of soil CO_2 concentrations.* The first *in situ* measurements of soil CO_2 concentrations were made by Boussingault & Levy (1852, 1853) at depths ranging from 40 to 240 cm. Using sophisticated equipment to avoid contamination of soil CO_2 by atmospheric CO_2, these authors showed that CO_2 concentrations in soils without farmyard manure (FYM) application were 22 to 23 times higher than in the atmosphere, and that applying FYM could increase this concentration by 245-fold. Wollny, in his book on SOM decomposition (1902) inventoried the effect of different environmental factors on soil CO_2 concentrations. He demonstrated the positive effects of soil temperature and humidity on CO_2 emissions, and showed that any agricultural or environmental factor that influences soil temperature and humidity has an effect on CO_2 fluxes.

According to Waksman (1938) the first measurements of soil CO_2 emissions in laboratory and controlled conditions were done by Ingen-Housz (1794–1796), who demonstrated the effect of organic inputs and the importance of oxygenation, temperature and humidity. As early as 1855, Corenwinder (1855; 1856) used equipment very similar to today's respirometry apparatus. The technique was largely used by Dehérain & Demoussy (1896*a*, *b*), Wollny (1897) and Stoklasa and Ernest (1905). The latter proposed the measurement of CO_2 evolution as an indicator of the availability of SOM. In 1920, Lemmermann & Wiessmann (1920) proposed a mathematical model for CO_2 production under laboratory and controlled conditions as an exponential function of time and of the initial concentration in soil CO_2.

Measurements of CO_2 fluxes at the soil–plant–atmosphere level

Lundegårdh's studies at the plot scale. The main forerunner to modern measurements at this scale was the Danish ecophysiologist Henrik Lundegårdh (1888–1969). His summarized biography was recently published by Larkum (2003). Between 1924 and 1930, Lundegårdh published considerable data on CO_2 fluxes at the soil–plant interface in two books (1924, 1930) in German and a large paper (1927) in English.

In these three publications, Lundegårdh reports an impressive amount of quantitative data on *in situ* CO_2 fluxes between atmospheric, plant and soil components. Data were collected using instruments for the sampling of the soil atmosphere (equivalent to our present static chamber) or continuous monitoring of CO_2 fluxes at the plant or atmosphere level. In his 1927 publication, he even described field equipment and experimental designs completely equivalent to the present-day 'free air CO_2 experiment (FACE)', which are among the most sophisticated experiments for the study of CO_2 fluxes in the field. FACE experimenters, however, seldom refer to Lundegårdh's remarkable pioneering work. Lundegårdh's findings are also notably close to present data concerning

CO_2 fluxes for the soil–plant system, and can be summarized in the following points:

(1) an increase of 0.01–0.32% in the atmospheric CO_2 concentration can change drastically the plant C assimilation rate, which is dependent on illumination and temperature;
(2) large monthly and interannual variations in air and soil CO_2 concentrations can be observed, for a given location and soil;
(3) soil CO_2 emissions vary depending on soil type, and range from 1.25 to 23.4 kg CO_2 ha^{-1} h^{-1};
(4) soil CO_2 production decreases strongly with depth.

His work on the effect of soil management on CO_2 fluxes showed that:

(1) the relationship between CO_2 emissions and SOM content is not completely direct;
(2) organic inputs lead to large and persistent (up to a year long) increases in CO_2 emissions;
(3) mineral fertilization significantly increases soil CO_2 emissions, due to a priming effect on SOM mineralization, and this increase contributes indirectly to better plant C nutrition, in addition to the positive fertilization effect on plant productivity.

All these questions are currently topical with regard to quantitative knowledge about the effect of land use and land-use change on the global CO_2 balance.

From the square metre scale to the hectare scale. The eddy covariance (or eddy correlation) technique is commonly used for the estimation of CO_2 fluxes in continuous natural or cultivated agro-ecosystems at the plot (≥1 ha) scale. A recent and exhaustive historical review of the results obtained by this new approach was published by Baldocchi (2003) and need not be repeated here. This technique can also be applied at the cultivated plot scale (100 m^2), and was used by Reicosky *et al.* (1997) for the study of the effect of soil tillage on soil CO_2 fluxes.

Assessment of soil C stocks and dynamics at different scales

The dynamics of the soil compartment are heavily implicated in the impacts of land use, land-use change and forestry (LULUCF) on the atmospheric GHG budget. The soil may act as a sink (by SOC accretion and CH_4 absorption) or a source for C–CO_2 in the medium term (0–50 years). There has thus been a growing need: (1) to quantify present SOC stocks at different spatial scales, from the plot-scale to continent-wide); and (2) to predict its dynamics in response to LULUCF, using simple and robust mathematical models.

Evaluation of SOC stocks. The content of OC, OM or humus in soil was determined as early as the beginning of the nineteenth century, as Thaër's Humus Theory (1809) shows. The emergence of the soil C sequestration issue has resulted in a large effort to acquire databases of SOC stocks at scales from the plot to the globe. Table 3 summarizes the historical data on the evaluation of SOC stocks at the global scale. The first publication was probably that of a geologist, Lyon, as early as 1915 (Rubey 1951). His study was based on nine soil profiles only (for the whole planet!) but his estimate (710 Gt C for the 0–100 cm layer) was reasonably close to Batjes's modern (1996) result (based on 4353 soil profiles) of 1500 Gt C for the same depth. Similarly, the global estimates of Waksman (1938) of 400 Gt C, for the upper 30 cm of the soils are also close to that of Batjes' (1996) 684–724 Gt C for the same soil layer.

The need to model SOC dynamics. The first qualitative approach for modelling SOM dynamics was by H. B. de Saussure in his famous *Voyages dans les Alpes*, §1319 (1780–1796). Extracts were republished by his son, N. T. de Saussure, in his book *Recherches Chimiques sur la Végétation* (1804). They were based on observations made by his father during a journey traversing the plain between Turin and Milan – a region cultivated since antiquity. These observations and reflections can be summarized as follows:

(1) since no continuous accumulation of SOM occurs, even with continuous organic inputs, some of these inputs must be destroyed;
(2) the amount which is destroyed must, to a certain extent, be proportional to the absolute existing amount;
(3) limits to SOM accretion must vary depending on climate, the nature of the bedrock, vegetation, the cropping system and the fertility of the land;
(4) even if all the conditions are favourable to SOM accumulation, there must be a maximum for the thickness of the humus layer, beyond which destructive causes equal productive ones.

Table 3. *Publications including an evaluation of SOC stocks at the global level*

Authors	Year	Number of profiles	Results for soil profile (Gt C)			
			Soil layer			
			0–100 cm	Litter included: yes/no	Other	Depth in cm
Waksman	1938	n.d.			400	(0–30)
Rubey*	1951	9			709	(0–?)
Bohn	1976	*c.* 200	3000	(n.d.)		
Bohn	1982	187	2220	(y)		
Post *et al.*	1982	2696	1395	(n)		
Eswaran *et al.*	1993	1000 (world) + 15 000 (USA)	1576	(n)		
Sombroek *et al.*	1993	400	1220	(n)		
Eswaran *et al.*	1995	1000?	1576	(n)	652	(0–25)
					927	(0–50)
Batjes	1996	4353	1462–1548	(n)	684–724	(0–30)
					2376–2456	(0–200)
Jobbágy & Jackson	2000	2721	1502	(n)	1993	(0–200)
					2344	(0–300)

n.d.: not determined.
* Rubey (1951) used SOC contents for 9 main soil types published by Twenhofel (1926) based on values reported by Lyon *et al.* (1915).

H. B. de Saussure's conclusions, completely ignored by historians of soil science, thus convey the basic equilibrium concepts utilized by modern mathematical models of SOM dynamics. Yet it was not until 137 years later that a mathematical formulation of SOM (C or N) dynamics for the decrease in organic N content with cultivation was to be expressed by Jenny (1941), followed by the more general model of SOM dynamics proposed by Hénin & Dupuis (1945). Many models have now been published and are being used (Smith *et al.* 1997). The most famous ones are probably the RothC model of Jenkinson & Rayner (1977) and the Century model of Parton *et al.* (1987). These models were designed to run at the plot level. Coupling them with geographical information systems (GIS) in order to simulate changes in SOC storage at scales from the plot to global, is the ongoing challenge faced by investigators of global change.

Towards an economic value for SOM?

The range of benefits in terms of 'goods' and 'services' provided by the SOM functions (Table 1), indicates that this resource is of great value to humans. This value is, however, only poorly comprehended by society in general – one of the major reasons being that it is not generally expressed in cash terms. In recent years, economists have intensified attempts to provide economic values for natural resources. In most cases, these values must be attributed *indirectly*, on the basis of the 'support service' provided for marketable products, rather than a *direct (i.e. cash) value*. Nonetheless, soil organic carbon has finally come to have a recognizable direct value. Because of the regulations requiring public and commercial organizations to reduce their contributions to global climate change, mechanisms have been sought for sequestering carbon in vegetation or soil as described on p. 14. Institutions which are net producers of carbon-based greenhouse gases have therefore entered into trading agreements with institutions that are able to sequester carbon. Carbon traded in this way is currently offered on the world markets for between 5 and 20 US\$ t^{-1}. The viability of this market for sequestrable carbon remains to be proven, however. The economic implications of locking farmers and other land users into long-term storage of carbon at relatively high levels, which may exclude a range of potential land-management practices, are far from apparent. Trading in carbon over the long term is also dependent on the acceptance by all parties of methods for measuring and monitoring carbon change. Such standards are not yet in place, and indications are that the costs may render the trading uneconomic (Smith 2004). Apart from the vital issue of sensitivity for tracking presumably low and slow variations in soil C density, one requirement for establish monitoring systems for soil carbon, whether for its role in GHG mitigation or for other environmental services, is to have acceptable methods for establishing thresholds or boundaries as minimum – and perhaps also maximum – values for SOM content, values below which agricultural and ecosystems services cannot be achieved. The above review of methods for measuring soil carbon indicates that this still remains a major challenge.

One recent attempt to achieve this was made by Feller (1995) for annual cropping systems on low-activity clay (LAC) soil in the sub-Saharan West Africa (sahelo-sudanian region). This resulted in a simple equation for calculation of threshold values of SOM content, expressed on a SOC basis of the 0–10 cm layer in relation to soil texture (percent clay + silt content, $c + s$, in g 100 g^{-1} soil), i.e.:

$$\text{SOC (g kg}^{-1}\text{ soil)} = 0.32\,(c + s\ \%) + 0.87$$
$$(r = 0.97, n = 15)$$

Below this threshold soil physical, chemical and biological properties are very low and plant yield severely inhibited.

The value of SOM goes beyond its significance in mitigating climate change. The other benefits do not, however, carry such a recognizable market value. Most would probably agree that the greatest benefit of SOM derives from its contribution to soil fertility and thence to the production of food and fibre. These contributions are indirect, in the sense that SOM is not itself a product, but has properties (as a source of nutrients, through improving the water storage capacity of soil, etc.) that contribute to enhanced crop production. Economic methods exist for making estimates of such *indirect values* (e.g. see Perrings 1995). Such estimates remain to be made for SOM, but the principles seem to be well established. The basis lies in calculating credible contributions of SOM to services that can be given a value, e.g. crop production. This is not a trivial task, but it can be approached through crop production models.

These calculations are very common at the farming-system level, but have not generally been used for the purpose of estimating the SOM value. These approaches are, however, not new. In the nineteenth century, the quantification of the economic value of SOM for fertility was a large component of Thaër's system, with the humus theory being used as a tool to predict not only the productivity but also the cost/benefit of SOM management. For instance, rye productivity was used as an indicator for the biological and economic evaluation of different management models proposed by Thaër (Feller *et al.* 2003). This analysis included all the costs (labour, space, care of animals) of organic maintenance of fertility, based on fallowing and manure application.

Similar modelling approaches could be used to estimate the value contributed by SOM to other ecosystem services, such as its contribution to erosion control. A number of well-known biophysical erosion models include an economic output (e.g. the EPIC model, Williams 1989; Jones *et al.* 1991). A major challenge in this work is to quantify the SOM contribution to processes that are also influenced by many other factors.

Values can also be given to resources for their *future* (sometimes known as *optional* or *serependic*) *values*, i.e. their potential to yield benefits in the future as well as any realized today. Thus, a value might be attributed to retaining SOM at a level which ensures its ability to store additional carbon in the future, i.e. to pay today to avoid jeopardizing future utility.

Despite its obvious functional significance and importance, it is difficult to assign a cash value to SOM from the benefits that it provides. Alternatively the *existence* or *non-use value* is the value that we may be prepared to give something, simply on the basis that we welcome the knowledge that it exists. In the same way, people express their 'willingness to pay' for the maintenance of key species of the world's biodiversity, such as pandas and rainforest trees, they may also be willing to do so for the existence of a living healthy soil. There may be people who simply like to see and to smell a beautiful humus horizon in the forest, or get pleasure from the view of furrows in the cultivated fields after tillage. The Flemish painter, Brueghel the Elder, enjoyed painting cultivated landscapes exhibiting, for instance, his appreciation of a well-tilled soil in the *Fall of Icarus*. Philosophers and writers on nature, such as those involved in the organic farming movement (e.g. Steiner 1924, or Rusch 1972) have attributed a clear 'existence value' to SOM by considering humus as one of the 'principles of life'.

Conclusions

As shown above, there is a long history of scientists' engagement in the study of SOM, SOC or the C cycle, as a consequence of their being convinced of its functional value. There are many cases, often forgotten, of perceptions that prefigure present-day concepts accepted as essential for sound management of natural resources, such as that of sustainability (e.g. Thaër and his system for predicting the sustainability of a farming system). Moreover, these ideas have often been based on the development of new approaches (such as modelling) and tools (such as FACE-type experiments) which are readily recognizable by present-day scientists.

Today's agronomists and ecologists are concerned about the impacts that human activities have on SOM. It is now generally accepted by scientists that loss of SOM is one of the major factors leading to degradation of ecosystem services and loss of ecosystem resilience. In many countries, however, conflicts have arisen, between policies for ecosystem protection that embrace sustainable soil management, and those targeted at agricultural development. These conflicts are often blamed on the ignorance of decision-makers, but scientists must accept that they have an equal responsibility to ensure that their knowledge is shared in an accessible way: society is unlikely to embrace these issues unless it is convinced of the economic value of SOM. The key to this persuasion rests on our capacity to demonstrate that SOM is a major and essential component of ecosystem functions and services and must be conserved and sustained by appropriate ecosystem management practices.

The authors acknowledge helpful reviews by Ken Giller and Roel Merckx. This work received financial support from the Institute of Research for Development (IRD) and the Institute of Forestry, Agricultural and Environmental Engineering (ENGREF).

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