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Review

Historical evolution of soil organic matter concepts and their relationships with the fertility and sustainability of cropping systems

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Abstract

Soil organic matter (SOM) is understood today as the non-living product of the decomposition of plant and animal substances. Because it is now recognised that SOM tightly controls many soil properties and major biogeochemical cycles its status is often taken as a strong indicator of fertility and land degradation. Nonetheless the building of the SOM concept has not been easy. A reason for this is that the SOM concept is the product of interdisciplinary cognitive production as well as of a cultural moving context. Historically, three periods involving SOM in relation to cropping sustainability can be distinguished. (1) Until 1840, some still believed that plant dry matter was mainly derived from uptake of matter supplied by SOM, which was termed humus at that time. Agriculturists who believed this based the management of cropping systems fertility on the management of humus, i.e. through organic inputs. In 1809 Thaër proposed a ‘‘Humus Theory’’ that remained very influential for 30 years, as well as a quantified assessment of the agro-ecological and economic sustainability of farming systems. (2) From the 1840s to the 1940s, Liebig’s ‘‘mineral nutrition theory’’, progressive abandonment of recycling of nutrients between cities and country, and breakthroughs in the processes of fertilizer industry paved the way for intensive mineral fertilization as a substitute for organic practices. Although understanding of SOM and soil biological functioning was improving it had little impact on the rise of new mineral-based cropping patterns. (3) Since the 1940s, SOM has been gaining recognition as a complex bio-organo-mineral system, and as a pivotal indicator for soil quality and agro-ecosystems fertility. This has resulted from: (a) methodological and conceptual breakthroughs in its study, leading to significant scientific developments in characterising the role of humus as an ecosystem component; (b) a growing societal demand for the assessment of the environmental cost of intensification in modern agricultural practices, which has led to growing interest in organic farming, agroforestry, conservation tillage, and the use of plant cover; (c) investigation of the potential of SOM as a sink for greenhouse gas carbon in response to concerns about global climate change. In summary the interest in SOM over time, both from the viewpoint of scientific concept and that of field practices, can be described by a sine curve. Its definition and the recognition of its functions have gained both much from the combination of holistic and reductionist approaches and from the progressive amplification of the scale at which it has been considered.

Keywords: Agro-ecology; History; Humus; Soil fertility; Soil organic matter; Sustainability

Contents

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1. Introduction

Soil organic matter (SOM) is now recognised by soil scientists as a major factor controlling the capacity of soil resources to deliver agricultural and environmental services and sustain human societies at both local (e.g. fertility maintenance; Fig. 1) and global (e.g. mitigation of atmospheric carbon emissions) scales (Tiessen et al., 1994; Syers and Craswell, 1995). This has not always been the case however and conceptualisation both of its nature and functions has varied greatly. For example, even today, the term ‘humus’ is frequently substituted for SOM, since it is recognized as the ‘‘*non-living*, *finely divided organic matter in soil*, *derived from microbial decomposition of plant and animal substances*’’ (Encyclopaedia Britannica, 1990). But this definition, whilst encompassing the fully re-synthesised nature of SOM, omits the less decomposed components that many soil scientists would include as the ‘light fraction’. This type of uncertainty is characteristic of fluctuations in meaning that have, over the last 300 years, reflected often radical changes in the perception of SOM and its methods of investigation by scientists and agriculturists.

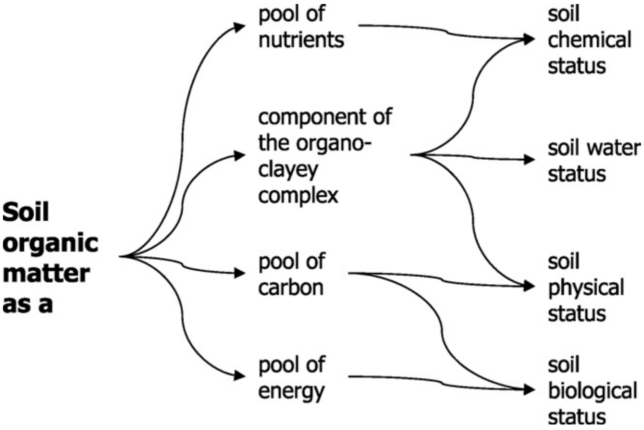

Fig. 1. Relationships between soil organic matter and soil fertility.

The first and best expression of SOM in terms of its multi-purpose dimensions and intimate connection with human history was probably that by Waksman in the conclusion ‘‘*Humus as an organic system*’’ from his masterwork ‘‘*Humus. Origin, chemical composition and importance in nature*’’ (Waksman, 1938): *“The importance of humus in human economy seldom receives sufficient emphasis. Suffice to say that it probably represents the most important source of human wealth on this planet. Nature has stored in and upon the earth, in the form of humus, the source of a vast amount of readily available energy, a large part of the carbon needed for life processes, and most of the combined nitrogen, so much needed for plant growth”*. But this scientific recognition of the relationship between SOM, soil fertility and sustainability and its implications for farming practices have taken a long time to settle into accepted wisdom. Over time the main reasons for this have probably been due to: (1) difficulties in adequately defining concepts, (2) erroneous analysis of the specific agroecological functions of SOM (particularly the persistence of theories

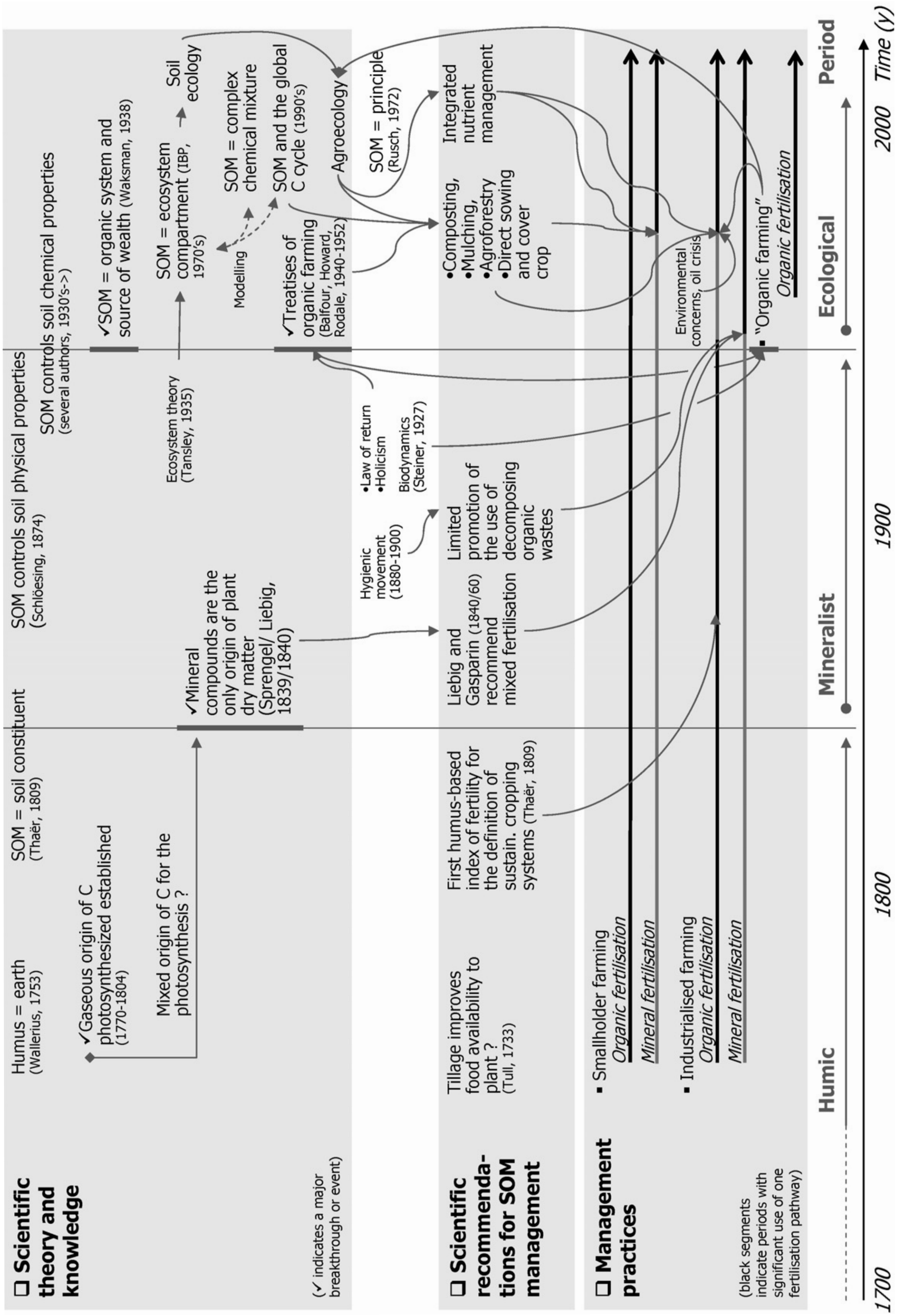

Fig. 2. Evolution of the soil organic matter concepts in relation with scientific recommendations for sustainable farming and management practices across the past 300 years.

of plant chemoheterotrophy in relation to carbon), and (3) the length of time it took before Waksman's systemic and organic view of SOM could be formulated and accepted (Fig. 2).

Such vicissitudes would not surprise historians and sociologists of science who are accustomed to the analysis of the building of a scientific concept such as soil organic matter. They recognise this process as a complex interaction between the elements of cognitive production, and the societal context, including economic and political facts and ideologies, and the cultural perceptions of environment—whether mainstream or alternative (Latour, 1988; Boulaine, 1989). This type of analysis was recently applied for example to a closely related set of issues to do with tropical soil fertility (Latour, 1999; Keeley and Scoones, 2000; Wincklerprins, 2002). The purpose of this paper is to present an account of the evolution of concepts of soil organic matter (and the related concept of humus) not only to establish an important historical record but also to illustrate the complexities of scientific progress through the example of a fundamental component of soil science that has been addressed by many of its most influential proponents. It is an underlying assumption that present day science is better conducted with an understanding of the past.

The hypothesis with respect to the analysis of the evolution of the SOM concept in this work is that the building of this concept has not been solely a process endogenous to soil science, but that it is also a social construction. To show the interdisciplinary and social legacies embedded in the SOM concept the paper focuses on its relationships with the development of understanding of soil fertility and the sustainability of cropping systems. To explore this hypothesis the paper analyses first changes in the definition of the concepts of ''humus'' and SOM and then explores the relationships between SOM, fertility and sustainability in both agricultural science and farming practices over the last 300 years. Although the history of soil science reveals the evolution of knowledge about SOM as a rather continuous process of interwoven discoveries and recurrent debates, three periods can be usefully distinguished in the scientific perception of SOM: ''the humic period'' (before 1840), the ''mineralist period'' (with the approximate dates of 1840–1940) and the ''ecological period'' from 1940 up to the present time. The first two periods are closely related to the evolution of plant nutrition theories, while the third is characterised by a widening of the perception of SOM's contribution to ecosystem function and human well-being.

2. Historical meanings of humus, a precursor for soil organic matter

The first occurrence of the term ''soil organic matter'' in science cannot be dated with any precision. The term ''humus'' may well be considered as its precursor, although it has encompassed a wide range of meanings, which relate it more or less closely to modern understandings of SOM. The etymology of the word humus is Latin, and has been used to describe three substantially different concepts: humus as a chemical constituent, humus as a horizon and, less frequently, humus as a principle (Feller and Boulaine, 1987; Feller, 1997a).

To Roman writers (Virgil, Pliny the Elder and Columella), ''humus'' meant ''soil'' or ''earth''. Thus, Virgil named loamy soil ''*pinguis humus*'' and used the words ''*humus*'', ''*solum*'' or ''*terra*'' interchangeably to convey the notion of soil or earth rather than restricting the meaning to soil organic matter. At the beginning of the 1st century, after Cicero (106–43 B.C.), ''humus'' in the sense of ''soil'' progressively died out and was replaced by ''*terra*'' (Martin, 1941).

Humus probably re-entered the European scientific vocabulary in the 18th century. It appeared in Diderot and d'Alembert's Encyclopaedia (1765, vol. 8), with the meaning ''*mould, garden earth, earth formed by plant decomposition*''. However, humus was not immediately assimilated into scientific (naturalist or agricultural) terminology, which implies that its use was not widespread at that time. It was used for the different meanings of soil, surface organic horizon, or soil organic constituent, but specific details were not given. Until 1781 the word ''humus'' was seldom cited. In his mineralogical classification, Wallerius (1753) used it as a Latin word for ''loam'' or ''mould'', and Valmont de Bomare (1768) used it in the sense of ''soil'' or ''soil horizon''. Between 1781 and 1809, the Latin word ''humus'' passed into French. Humus was widely used throughout the ''*Cours d'Agriculture*'' by Rozier (1781–1805), but was not indexed under the letter H, which probably indicates that the term was still rarely used. At that time it still lacked precision, denoting either ''vegetable mould'', ''mould'' or ''constituent''. For Patrin (1803), ''humus'' still referred to ''soil'' but to Virey (1803), it meant ''*remains of organized bodies*''. De Saussure (1804) ascribed a broad meaning to the word ''humus'' (the whole vegetative cover undergoing decomposition) and a narrow meaning to the word ''mould'' which referred to ''*the black substance plants are imbedded in*''.

2.1. The ''humus-horizon'' concept

The ''humus-horizon'' concept appeared very early but its use only became widespread during the 19th century in connection with forestry research and the emergence of soil science. Wallerius (1753) is usually credited with presenting the first ''mineralogical'' classification of humus. According to Wilde (1971), Hundeshagen (1830) was the first to introduce a morphological classification of forest humus, quoting two types of humus with different effects on silviculture. In 1875, Emeis in turn described two humus types: one formed from organic materials incorporated in the mineral soil (the present-day mull), another one from bulk and raw organic remains. At about the same time, Ebermeyer (1876) carried out a detailed study on forest humus in Bavaria, and provided a classification of forest humus as: "fertile" humus, "dust or peat" humus, "acid" humus, and "astringent" humus. But it was Müller in his noteworthy works (1879; 1884), who laid the foundations for the present day scientific studies on the different forms of humus characterising forest horizons (Feller et al., 2005; Feller et al., 2006). His book, "*The natural forms of humus*" (1889), is a treatise on the changes of brown soils to podzols; its distinction of different types of humus horizon (beech forest "*Mull*"—mould and "*Torf*"—peat) can still be considered valid today. The book also contains detailed descriptions of soil profiles, the results of microscope studies, a number of mechanical and chemical analyses, and a comprehensive, quantified study of the litter decomposing organisms, mycelia and earthworms.

The different forms of humus are based on the existence of two stages in the humification process: "*The mechanical division of organic remains ... and ... the mixture of organic remains and mineral earth*", which significantly preview modern concepts (Swift et al., 1979). Thus with respect to uncultivated soils, Müller's studies, together with those of Darwin (1837, 1881; see Feller et al., 2003a,b) initiated the concept of a biological basis to soil development. The word "humology" was even proposed in place of "soil science" (Hamor, 1929 quoted by Waksman, 1938). After Müller the "humus-horizon" concept was further developed to include different classifications of humus (Ramann, 1893; Henry, 1908; Kubiana, 1953; Wilde, 1954; Duchaufour, 1956; Wilde, 1971; Delecour, 1980 among others).

2.2. The "humus-constituent" concept

The "humus-constituent" concept first appeared in 1809 when the word was used by Thaër, in the sense of soil component in his "*Principles of rational agriculture*", which was first published in German (1809) then in French (1811), then in English (e.g. the American edition, 1856):

"The name usually given for this substance is "mould". This term has been widely misinterpreted by many persons, who have understood it to mean the layer of vegetable earth, and not a particular portion of its constituent parts. Several very clever agricultural writers have fallen in the same error; and thus the obscurity which enveloped this part of the science has been increased ... (Humus) is the residue of animal and vegetable putrefaction, it is a black body..." (American edition, 1856). This conception of humus is very close to the current definition of SOM.

2.3. The "humus-principle" concept

The soil biota (plant, fauna and micro-organisms) occupies an important place in the "humus-horizon" concept. For example, the conceptual association between SOM and life is one of principles underpinning organic farming theories. Rusch's "Soil Fertility" ("Bodenfruchtbarkeit", 1972) presents a holistic and philosophic perception of humus as a basis for some of these theories where humus is "*the biological and functional power of living substances to organize the wastes of living beings in a new harmony... it is the expression of effective relationships between the living earth and other organisms*" (translated from French). According to Rusch, humus is not just what remains (i.e. humic substances) in soil after the decomposition of fresh organic matter. It also includes all plant, animal and other microbial bodies that have previously decomposed. In Rusch's opinion, "*the "humus" concept has (historically) deteriorated from a biological process to a mere residue*". Describing humus as a substance, Rusch asserts that "*it forms a living primitive tissue, an original form made up of a congregation of mineral, organic and living substances*", and concludes: "*In short, Humus is a principle, an original force, the driving force behind fertility*".

The changing meanings of humus, that have invariably carried wider dimensions than the present sense of soil organic matter (Fig. 2), reflect the evolution in the understanding (and means of understanding) of: (1) the nature and roles of SOM by scientists and to some extent of its management by agriculturists, in a way which is explained below and (2) the changing human perception of, and relationship with, nature and the environment.

3. The humic period (before 1840)

3.1. The pre-19th century debate

In Ancient Greece and Rome, soil fertility referred to its physical rather than chemical properties. Plants were assumed to feed on organic material preferably derived from the same species; for instance, olive stones were brought to olive trees, and vine shoots to vines to sustain plant production. Such beliefs were still held during the Middle Ages. Palissy, 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; however, since Palissy's definition of "salt" is not strictly mineral, this opinion is questionable (Feller et al., 2003b). In the 17th century Van Helmont, 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).

During the 18th century "humus" was often understood to be soil, and many theories about plant nutrition were based on the belief that plants relied directly on humus for their own carbon supply. Consequently, some authors adopted ambiguous terminology and referred to "juices", "oils", or "bituminous substances" (Valmont de Bomare, Pluche, Home, Duhamel du Monceau, La Salle de l'Etang, Bonnet, Rozier; see: Feller and Boulaine, 1987; Feller, 1997a,b). Tull (1733) proposed a "new agriculture" and fertilization practices based on soil tillage carried out as frequently as possible, in the belief that since soil particles were a source of food for the plant, the texture of the soil had to be fine to enhance uptake by roots. On the other hand, by the end of the 18th century several authors – all cited in Bourde, 1967 – for example Priestley (1777), Fabbroni (1780), Ingen-Housz (1780), Senebier (1782) and de Saussure (1804) denied these theories and experimentally demonstrated the gaseous origin of carbon and the role of light in photosynthesis. Contradictory debates arose on the subject, especially between Hassenfratz (1792a,b) and Ingen-Housz. Without referring to experimental facts, Hassenfratz re-asserted the theory that a fraction of humus in the form of soluble carbon is directly assimilated by plants (i.e. carbon heterotrophy).

3.2. Thaër's theory of humus, integrated analysis of fertility management and the perception of sustainability

Thaër's "*Principles of Rational Agriculture*" (1809) contains some unverified theoretical developments on plant nutrition that served as a basis for the first rational and systemic approach to fertilization within the context of sustainable cropping practices (de Wit, 1974; Feller et al., 2003b). For this reason, he deserves particular attention. His book was released during a period of controversy over the source of carbon used by plants i.e. whether soil or atmosphere. Thaër did not deny that atmospheric CO_2 could be a carbon source for the plant, but since this compartment seemed unlimited, he considered SOM and its management as the main limiting factor on plant carbon nutrition. So, unfortunately, Thaër derived his theoretical basis for plant nutrition from Hassenfratz' ideas (1792a; 1792b) rather than from the works of de Saussure (1804) (to which he refers only in the sense which best fits his theory). According to Thaër: (1) the majority of plant dry matter derives from the "soil nutritive juices" contained in the fraction of SOM that is soluble in hot water (the rest deriving from CO2 but being out of farmer's control); (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 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 soil fertility.

Thaër's main contributions were the precision of his definitions and by use of both bibliographic and experimental sources in his effort to quantify certain principles of rational agriculture. He created an analytical tool based on an index of innate soil fertility ("natural fecundity") ranging from 0° to 100° computed from an empirical function of soil texture (clay and sand contents), and the contents of lime and humus. Fertility degrees would then be added or subtracted depending on crop species, organic fertilization (fallowing and manuring intensities) and yield (Feller et al., 2003b). Thaër computed his fertility index for several cropping systems, and thence ranked them with regard to their agricultural sustainability (although this concept did not exist at that time). To optimize the economic value of this system, Thaër suggests that cash crop production be substituted by some forage production, which would keep the soil fecundity level at its initial value. This is probably the first example of real concern with – and attempt to measure – farming 'sustainability'. Naturally enough, in view of his theories on humus it is based on organic practices. One of his disciples, C. von Wulffen (1823, in de Wit, 1974), whilst sticking to the systemic and organically centred approach, suggested that the use of Thaër's fertility index was not needed to quantitatively model farming sustainability, and thus simplified the dynamic properties of Thaër's model.

Thaër's analyses also included economic appraisals of existing farming systems using the same range of cropping patterns and including all costs (labour, space, care of animals) of the organic maintenance of fertility based on fallowing and manuring.

Conceptually, Thaër's approach to fertility encompassed the plant–soil system as well as cropping patterns and rotations. In doing so he tackled modern agricultural issues such as the identification of soil quality indicators, systemic analysis and the agro-economic sustainability of farming systems. His work seriously influenced the thinking of his peers during the first half of the 19th century. If Thaër had focused on mineral rather than organic budgets he would probably have been regarded as the founder of Western scientific agriculture.

4. Soil organic matter in the mineralist period (1840s–1940s)

The end of the 18th century had seen the pioneer studies that had identified the role of light and carbon dioxide in carbon assimilation by plants and the release of oxygen as its by-products. A corresponding shift can be seen towards the middle of the 19th century in the works of Martin (1829) and Boussingault (1838, cited by Grandeau, 1879, reference not given) with respect to the scientific conception of the role of SOM in plant nutrition. This shift was not abrupt however: these authors granted SOM an indirect role as a source of carbon dioxide during photosynthesis. In fact, in those days, many agricultural scientists shared an intermediary point of view and assigned a function in plant nutrition to both SOM and air.

4.1. Sprengel–Liebig's mineral nutrition theory

Liebig's authoritative "*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, leading to the conclusion that carbon comes from carbon dioxide, hydrogen from water and other nutrients from solubilized salts in soil and water—although Liebig, who was gifted for synthesis, took much of his ideas from the work of Sprengel (Sprengel, 1838 in van der Ploeg et al., 1999) and others. Since Liebig's synthesis accounted rather satisfactorily for the fertilizing effect of mineral inputs, it provided the basis of modern agricultural science. Liebig promoted the use of fertilizers to compensate for soil mineral depletion and his work, together with that of Lawes and Gilbert at Rothamsted (e.g. see Dyke, 1993) paved the way for recommendations for the widespread use of chemical fertilization in cropping patterns.

The mineralist theory was developed in a context of the demands of growing urban populations located in areas increasingly remote from those of plant production, and with increasing reliance on foreign food and fertilizer production (Hyams, 1976). Agricultural scientists had thus no difficulty adopting Sprengel and Liebig's viewpoints on ''mineralism''. However, putting the theory into practice was hampered by the limited knowledge of phosphorus and potassium sorption, and by Liebig's wrong early assertions concerning the gaseous origin of the nitrogen (N) incorporated into the plant (Browne, 1944; de Wit, 1974), in contradistinction to Lawes who in 1846 challenged Liebig's view that ammonium was not important as ''*there cannot be a more erroneous opinion than this, or one more injurious for agriculture*'' (cited by Dyke, 1993). The sustainability of dependence on mineral fertilization alone was debated very soon after Liebig's ideas became widely known. Ville (1867) was among the most enthusiastic supporters of inorganic fertilization as a viable alternative to manure, which he thought was of no use for crop production. Grandeau (1878) on the other hand, warned against Ville's assertions. As an advocate of mixed fertilization, he suggested that SOM was vital for plant growth, since it increased the solubilization of mineral nutrients and thus their bioavailability to plants—a new concept. Liebig, as ''*one of the last* ''complete'' *men among the Great Europeans*'' (Hyams, 1976), sent Grandeau a congratulatory letter expressing full agreement with Grandeau's viewpoint. In the sixth volume of his exhaustive ''*Cours d'Agriculture*'' Gasparin (1860) took a similarly moderate position: he included organic and chemical fertilizers in the same category, but emphasized the low economic cost of organic fertilizers produced on the farm. In fact, the limited references to chemical fertilizers in Gasparin's textbook are partly due to the limited production and use of inorganic fertilizers before the 1880s (Boulaine, 1989; Smil, 1999). At this time the recycling of organic matter (OM) was also still considered a transcendental necessity rooted in theological beliefs (Mårald, 2002). Influential thinkers and scientists – including Liebig – and land use planners saw it as a way to clear up growing and filthy cities from their toxic organic wastes. As such its promotion was still vivid.

Finally, direct but very limited absorption of some organic compounds by plant roots was to be demonstrated in the early 20th century (Acton, 1899; Mazé, 1899, 1904, 1911; Laurent, 1904; Cailletet, 1911; Knudson, 1916 all cited by Waksman, 1938).

4.2. The origins of the multi-functional concept of SOM

The ''mineralist'' theory (Section 4.1) and – above all maybe – the hygienic movement that arose from the 1880s onward and that opposed closed sewage systems enabling nutrient recycling from the town to the country (Mårald, 2002) had a prominent influence on the definition of new organic-free cropping patterns during the second Agricultural Revolution. However knowledge about SOM underwent a significant breakthrough as early as the 1870s.

4.2.1. Biogeochemical cycles and C and N mineralization

Ingen-Housz (1794, 1796) was probably the first to measure SOM mineralization in laboratory experiments through CO_2 emission, followed by Boussingault and Levy (1852, 1853) who made the first *in situ* measurements of soil CO_2 concentrations at depths ranging from 40 to 240 cm. Using sophisticated equipment to avoid contamination of soil CO_2 by atmospheric CO_2, they showed that CO_2 concentrations in soils without farmyard manure application were 22–23 times higher than in the atmosphere, and that applying farmyard manure could increase this concentration by 245-fold. An even more important and innovative study was that of Wollny (1902) on SOM decomposition, since he demonstrated experimentally the links between soil biological – especially faunal – activity, soil physical properties and organic matter decomposition. Nitrogen mineralization also became a subject of study with the experiments of Schloesing and Müntz (1877a,b) and Lawes and Gilbert in the 1880s (cited by Dyke, 1993). In particular Schloesing and Müntz used chloroform as an antiseptic agent in their famous sewage treatment experiment, which demonstrated the major role of bacteria in the nitrification process. This can be considered as the first evidence for what is now termed the microbial biomass. These breakthroughs failed however to combat the influence of other contemporaneous findings on the association between micro-organisms and disease that supported the sanitary movement and its efforts against any handling of urban muck that would have favoured cropping patterns integrating the management of organic matter (Mårald, 2002).

4.2.2. Humus and the exchange and sorption properties of soil

The application of the notion of colloids to SOM (Berzelius, 1839; van Bemmelen, 1888) gave birth to studies on the exchange and surface properties of SOM by Gedroiz (1925, in Waksman, 1938), Tiulin (1926; 1927; 1938 in Waksman, 1938) and the emergence of the concept of an ‘‘organo-clayey complex’’ (Demolon and Barbier, 1927, 1929, 1933). Concerning the latter point, the first important work on the association between SOM and soil mineral particles is that of Schloesing (1874) described in Feller (1998). Schloesing observed that clay flocculation was a positive function of the SOM content. To identify which kind of SOM was responsible for the process and where it was located he conducted a particle-size fractionation of SOM and isolated and studied the organo-clay fraction. He observed that most of the total SOM was associated with clay and concluded that clay behaviour depended on the quantity of OM associated with it. This was probably the first example of the isolation of an organo-clay complex for the study of its properties.

4.2.3. Humus and aggregation

Schloesing (1874) was among the first to study the effect of humates on flocculation processes. In 1913, Dumont published his work ‘‘*Agrochimie*’’, a book seldom quoted and rather unusual since it is entirely based on the new concept of soil aggregates (‘‘*agrégats terreux*’’). It provides a detailed description of the formation, composition and properties of these aggregates. Dumont distinguished between skeletal or inert material, and cements. The organo-mineral composition of both the skeleton and cements was studied by chemical and physical fractionations. Two kinds of functionally distinct SOM were distinguished and related to their source (‘‘original’’ i.e. plant-derived versus ‘‘microbial’’). The microbial humus was identified as the ‘‘active humus’’, more involved in agrochemical cycles and especially nitrification. Studies on SOM, aggregation and soil conservation increased significantly later in the 1930s with the works of Tiulin (1933), Sokolovski (1933), Baver (1934), Anne (1935) and Myers (1937).

4.2.4. Other aspects

In his ‘‘*Humus. Origin, chemical composition and importance in nature*’’, Waksman (1938) lists several other functions of humus in addition to that of supporting agricultural production. These include solar energy storage, formation or decomposition of substances injurious or favourable to soil biota (plant/weed, fauna and micro-organisms) and the curative effect of organic complexes of SOM or soil organism origin on human beings (see recent review by Altieri, 2002). Furthermore, in his (previously cited) conclusion ‘‘*Humus as an organic system*’’ Waksman, characterising humus as a ‘‘*source of Human wealth on this planet*’’, proclaimed an era in which the agro-ecological role of SOM at both local and global scales would be fully appreciated, an era which came to pass after the intervention of the second World War.

5. Soil organic matter in the ecological period (1940–2000)

5.1. Further developments in the scientific concepts of SOM

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, subsidised 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 and Hazell, 1985). The same time period saw however the rise of a number of other scientific initiatives that, in contrast, resulted in renewed scientific and social interest in managing soil organic matter under the rubric of ‘sustainable agriculture’. These approaches can be seen as derived substantially from two convergent sources: developments in ecosystem science, including improved scientific capacity for the study of SOM and associated aspects of nutrient cycling; concerns about environmental degradation and the loss of ecosystem services, an important expression of which was the rise of the organic farming movement.

5.1.1. SOM as an ecosystem compartment

Tansley (1935) coined the term ecosystem to capture the concept of the interdependence between biological communities and their environment, although the virtually identical concept of biocoenosis (or geobiocoenosis) was already well established following the initial work of Mobius in Germany and its consolidation by the pioneering Russian soil scientist Dokuchaev and his followers (see Sukachev, 1944 for an account). A crucial step occurred when Lindeman (1942) proposed that the common currency underpinning all ecosystem processes and the interactions between organisms was that of energy transfer. This, and the link immediately made to nutrient cycling (e.g. see Ovington, 1962), gave birth to the era of ecosystem science, as acknowledged by the definition given by Evans (in 1956) that this addresses ‘*the circulation, transformation and accumulation of energy and matter through the medium of living things and their activities*’. The development of energy flow and nutrient cycling models of ecosystems was promoted during the 1950s and 60s by the work of the Odum brothers (see Odum, 1968, 1971) and broadened rapidly in the comparative ecosystem studies carried out under the International Biological Programme (IBP) (Worthington, 1975; Reichle, 1981). These studies quantified and clarified the importance of the ‘detritus food chains’ to the functioning of whole ecosystems, whether natural or man-managed. One consequence of the IBP was the emergence of soil ecology as an integrated discipline, building on the strong base laid in the earlier periods by Darwin (1837; 1881; see Feller et al., 2003a), and in particular Waksman in his Outlook ‘‘*Humus as an organic* *system*'' (in Waksman, 1938). Nonetheless the huge diversity of soil organisms and continuing uncertainty about their relative functional significance leaves soil ecology recognised as one of the ''last frontier(s)'' in the agricultural and ecological sciences (Andre et al., 1994; Altieri, 2002).

The proliferation of research into the processes of decomposition (see Swift et al., 1979 for a summary), building on the pioneering work of Waksman and his colleagues clarified the idea of SOM as a chemically distinct non-living '*product*' generated by biochemical processes during the decay of dead organic matter by living soil micro-organisms and animals. In ecosystem models SOM came to be pictured as a temporary but long-term 'storage' pool of energy, carbon and nutrients the size of which is the balance between its (biochemical) synthesis and (biochemical) decomposition. This concept thus emphasises the distinction between three different organic pools in the soil – detritus (the input), living organisms (the drivers) and SOM (the product) – and removes any property of 'life' from the latter. This distinction was further emphasised by the development of a method for the quantification of the living microbial biomass (Jenkinson, 1966).

Evidence gathered in the IBP strengthened the idea – previewed by de Horace-Benedict de Saussure in his ''Voyages dans les Alpes, § 1319'' (1780–1796) (cited by his son Theodore de Saussure, 1804) – that the equilibrium mass of the SOM pool is strongly influenced by the interaction of climate, parent material and vegetation and is a characterising feature of ecosystem types. This brought the conclusions of ecosystem science with respect to SOM into direct convergence with those of pedologists as characterised by the 'state factor' theories of soil formation promoted by Jenny (1941, 1961) which in their turn owed much to the work of Dokuchaev and his successors in Russia.

5.1.2. *SOM as a soil component*

At the same time that the status of SOM was being confirmed as a macroscopic compartment of ecosystems, its molecular and microscopic structure and dynamics were being further elucidated. Application of new techniques in organic chemistry (chromatography, analytical pyrolysis, nuclear magnetic resonance and the use of isotopes) confirmed SOM as one of the most complex of natural materials, a mix of molecules of varying polymericity and aromaticity (Skjemstad et al., 1997; Stevenson and Cole, 1999). Nonetheless the elucidation of the nature, synthesis and decomposition of SOM at a detailed process level remains a major scientific challenge.

One of the most important convergences between the ecological and chemical approaches has been the recognition that SOM can be readily conceptualised as a mixture of fractions differing in their rate of turnover (i.e. their decomposability). A wide variety of techniques, both chemical and physical (e.g. by size or density) have been devised to separate and characterise these fractions (Elliott and Cambardella, 1991; Christensen, 1992). Most particularly a convergence between the 'micro' level of SOM study and the ecosystem concepts has been realised in the construction of simulation models derived from the principles of decomposition science which predict soil organic matter dynamics at the plot, ecosystem or even regional scale (e.g. Jenkinson and Rayner, 1977; Jenkinson et al., 1987; Parton et al., 1987). These models distinguish at least two pools of SOM; one 'labile', releasing carbon and nutrients within a matter of months from formation; one or more 'stable' pools (which include SOM 'protected' from decomposition by association with clay particles) with turnover times in years or decades which are relatively resistant to decay. It has proved difficult nonetheless to establish clear equivalence between the fractions as defined by models with the chemical or physical fractions measured by soil analysis.

5.2. *Environmental concerns about high-input agriculture*

Beyond the conceptual debate about the substitutability of organic amendments by chemical fertilizers (Smil, 1999; Rigby and Caceres, 2001), societal criticisms concerning the sustainability of intensive farming arose as early as the 1930s, when the hypothesis, already expressed in the 18 and 19th centuries (Mårald, 2002) began to be reformulated of a connection between the decline in soil fertility, the quality of the human diet and human health (Balfour, 1944). The potential of chemical fertilization for increasing crop yield was widely recognized at the end of the 19th century, and industrial synthesis of N and processing of P fertilisers were mastered by the early 20th century. Agronomists at this time were still driven by the challenge of feeding growing world populations, in a context of non-limiting natural resources with little concern for environmental issues and of hygienic activism (Mårald, 2002). Mineral fertilizers did not account for more than 15% of nutrients utilised by crops in 1900, and even in 1940, in the economic context of recession and world wars, still played only a limited contribution to the second agricultural revolution. Indeed N fertilization practices in Europe largely relied on low-cost biological fixation and the relatively high nutrient capital of the soils (Boulaine, 1989; Smil, 1999; Mengel, 2000). During the first half of the 20th century, intensification derived mainly from laboursaving inventions (e.g. motorization) (Mazoyer and Roudard, 1997). Erosion, usually the most spectacular, immediate and irreversible symptom of inadequate agricultural practices, was the first indication of the drawbacks of intensified practices that left vast areas of soil deprived of the protection of plant cover. Its agro-economic cost was extensively quantified by Bennett (1939) for the Dust Bowl in the USA and by Jacks and Whyte (1939) (cited in Balfour, 1944) in the UK.

Thus the renewed interest in the study of SOM after the Second World War did not only stem from internal scientific dynamics. The cost of the post-war boom in the production of mineral fertilizers and more generally in the transportation of inputs for modern agriculture was assessed and criticized by Pimentel (1973) at the onset of the oil crisis. He – and later other authors such as Hall and Hall (1993), Izac (1997) and Tilman et al. (2002) – put forward objective criticisms concerning the true costs of substitution maintenance in modern agriculture. Scientific concern and societal demands for sustainable farming practices that would save non-renewable resources such as fossil fuel and nutrients, maintain soil agricultural and environmental functions, and be ecologically and economically relevant when applied to the whole planet, have led to the reassessment of the real value of biological maintenance of soil quality in agro-ecosystems (Izac and Swift, 1994; Swift, 1999) and to the reinsertion of organic cycling and SOM management in high input agricultural practices of Europe and North America (Gardner, 1998; Magid et al., 2001). These changes have taken place under circumstances where many parts of the world are free from hunger whilst others (notably most of Africa) with low use of fertilizers still suffer from levels of agricultural productivity well below that needed for food sufficiency. Soil fertility management must thus be adaptive to both sets of circumstances.

5.3. *Organic agriculture and concepts of SOM*

5.3.1. *Humus, SOM and the philosophy of the organic farming movement*

The above concerns (Section 5.2) about the impacts of high-input agriculture deriving from the formal scientific sector may have been however less important to the triggering of new interests in the management of SOM as a component of soil fertility than those that came from the rise of ‘alternative’ farming practices under the rubric of ‘organic agriculture’.

Concerns about the connection between loss of biological function and decreases in the fertility of heavily cropped soils managed without organic practices dates back to ancient times but the lack of sound principles of soil ecology diminished their impact on scientific thinking and land-use planning. Steiner’s lectures (1924) provided the foundation for biodynamic agriculture. The scientific basis of Steiner’s lectures and of the publications of his disciples (e.g. Pfeiffer, 1938) is low as they referred to both holistic and cosmogonic concepts (interrelations between stars, soil and geochemical elements, plants, animals and man) as the basis for a new kind of agriculture that excludes the use of any chemical input. The most influential – and more rational – publications on modern organic farming are those from Howard, Balfour and Rodale (Howard, 1940; Balfour, 1944; Rodale, 1945; Howard, 1952) (see Scofield, 1986; Lotter, 2003). The main objective 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.

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. She proposed a philosophy of organic farming that 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 Man at the top of the pyramid. Within this scheme, any degradation of soil quality can threaten civilization and even mankind itself, hence the need for careful soil husbandry.

Another principle of organic farming is the Law of Return. It stems from a concept of the “Living substances cycle” which originated in antiquity and reappeared in treatises on agriculture in the 16th and 17th centuries. It has been suggested that the breaking of this cycle may have accounted for the collapse of several civilisations that has been attributed to failures of their agriculture (Liebig, 1862 cited by Mårald, 2002; Wright, 2005; Hyams, 1976). The principle is regarded as underpinning a number of critical issues in urban waste recycling (Gardner, 1998; Magid et al., 2001; Mårald, 2002). According to this principle, life can be maintained only if living beings or at least the residues of their activity and the product of their 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 naive theory*” – probably referring to his early writings only – 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 quality of the cycling of proteins between living beings. Even if his opinions were partly ideological, Howard (1940, 1952) published rigorous and famous technical handbooks for the production of compost, which he termed “manufactured humus”.

5.3.2. *Limits to SOM-based farming schemes*

Today, in a world approaching critical limits to the availability of agricultural land, fertile soil and drinkable water, the desirability and feasibility of shifting from conventional, high-input practices to alternative ones are complex and passionate issues. For example low-input extensive practices that ‘mine’ soil nutrients have been implicated in land degradation and indirect damage to natural ecosystems (Borlaug, 2001) although there is abundant evidence that, despite having access to very limited quantities of nutrient resources, many smallholder farmers manage by ingenious practices to maintain niches of high fertility within their farms (Reij et al., 1996). Apart from the debate on sustaining soil productivity, controversies concerning organic fertilization include: (1) food security considerations, where deep controversy exists as to whether crop yields obtained by organic farming can compare with those obtained under conventional mineral-fertilizer based practices (Smil, 1999; FAO, 2002; Lotter, 2003); (2) the associated argument as to whether such practices, with their high demand for organic inputs, can be maintained, for example with respect to the increased economic and environmental transportation costs of organic fertilizers when the cycle of matter widens (Duesing, 1995; Rigby and Caceres, 2001; Tilman et al., 2002). These concerns with respect to the costs of organic agriculture must however be compared with the 'real' costs of current high, synthetic-input practices which have rarely been accounted for (Pretty et al., 2000; Pretty et al., 2001); (3) human health issues among which are those of the specific effects of harmful trihalomethanes derived from humic and fulvic acids following water chlorination (Haggblom and Bossert, 2003). All these points must also be set against the more general (and highly debatable) postulated differences in the quality of organically versus conventionally grown foods (Williams and Irish, 2002). The capacity to manage and sustain SOM as a key resource lies at the heart of these debates but the scientific basis of the issue is often ignored: at the extreme its role is treated on the one hand in ideological and almost mystical terms and in the other as irrelevant under conditions where its functions are by-passed by inputs.

5.4. 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 and 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 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 residues, composts or manures) and mineral nutrient inputs (Pieri, 1992). This rediscovery of the benefits of the ancient concept of integrated nutrient management has become the mainstay of soil fertility management practices at the turn of the 20th century (Mokwunye and Hammond, 1992; Palm et al., 1997) and maintenance and/or improvement of the organic status of the soil 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 and Giller, 1997; Smaling, 1998; Palm et al., 2001). Similarly the management of SOM has been enhanced by the application of the knowledge embedded in the simulation models mentioned above with a particular focus on manipulating the labile pools, whilst seeking to maintain or build up the stable SOM fractions (Vanlauwe et al., 1994). The major scientific challenge remains in extending the ecological principles beyond the manipulation of the plant component (with the consequent indirect influence on the soil biota, decomposition processes and humus dynamics) to more direct manipulation of the soil biota (Swift, 1998). Successes obtained with the nitrogen fixing bacteria (Giller, 2001) have still to be matched in other groups.

For the last two decades, general conceptual advances have stressed the aptitude of ecosystems – based on their internal organization – to escape constraints of the abiotic environment by building biotic buffers and 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 in the perspective of ecosystem rehabilitation (Perry et al., 1989; Aronson and 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 and van Keulen (1990). In fact, recent applications of 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 dissipation – mostly soil carbon-mediated – thus implicating SOM recycling (Perry et al., 1989). Therefore, a potential breakthrough in the study of SOM as a soil fertility indicator will most probably result from the combination of the traditional pool-based static perception and a new flow-based dynamic approach to SOM. This might for instance take the form of integrated modelling of the soil food webs and ecosystem functions including quantification of soil gaseous carbon and nitrogen emissions.

The modern concept of SOM within science-based sustainable agriculture as a dynamic, biologically regulated pool of energy, carbon and nutrients, converges with the concept of fertility defined for organic agriculture by Balfour as "*the capacity of soil to receive*, *store and transmit energy*" (Balfour, 1976 in Merrill, 1983). Nonetheless Howard (1952; p. 69), an early supporter of organic farming, was hypercritical of the "*intrusion of science*" in agriculture. Reciprocal suspicion about organic farming between scientists and farmers continued until the early 1980s, partly due to insufficient efforts to define the word "organic" and to use a single descriptive name for this kind of alternative agriculture (Merrill, 1983). However that may be, the distance between the understandings of scientists, the practical experiences of farmers, and the agricultural policies of governments has been progressively reduced since the 1950s, initially in the attitudes to organic farming, and latterly in the developments of scientifically generated designs for sustainable agriculture (Conway, 1997; Pretty, 2002). This has had the effect of enhancing the status of SOM management as a component of the design of new cropping schemes. In the Western World for instance, research stations devoted to organic farming founded as early as 1939 (Haughley Research Trust in UK, by Balfour), 1945 (Rodale Institute in the USA), 1950 (Germany) or the mid seventies (Switzerland, Netherlands) were originally privately funded, but are now partly financed by the state (Krell, 1997; Lotter, 2003). At a more global level, the International Federation of Organic Agriculture Movements, created in 1972, held its first international conference in 1977. Increased promotion or adoption world wide of precision agriculture, agroforestry (Steppler and Nair, 1987; Ewel, 1999), and of composting, mulching and direct sowing (CIRAD, 1999) testifies to the scientific value of integrated humus management for the definition of sustainable cropping patterns that were generally widespread before the mineralist era, but which have been conserved only in smallholder agriculture (Altieri, 2002; Jackson, 2002; Tilman et al., 2002). Similarly the incorporation of ecological concepts into modern agriculture, slow though it has been to grow, represents a return close to principles which were derived empirically from observation of nature, many of which have been retained in traditional indigenous knowledge in many parts of the world. This progress has been documented recently in a book (McNeely and Scherr, 2002), which celebrates the achievement of what the authors term 'ecological agriculture'.

5.5. *SOM, global change and ecosystem services*

Within the scope of global change related to human-induced release of greenhouse gases to the atmosphere, global carbon transfers from and to the soil have been receiving increasing attention for more than a decade (Schlesinger et al., 2000). The carbon pool in the world's soils is three times that in the atmosphere (IPCC, 2001). Any change in the belowground pools resulting from changes in land-use (conversion to crop or pasture, afforestation), can thus have major impacts on carbon concentrations in the atmosphere. Most of these carbon flows are mediated by SOM, and have led to the numerous studies of the carbon-oxidation to carbon-fixation balance in relation to land use and climate change. Whilst these studies are generally undertaken at the plot scale, they have been conceived and applied to the issues of global climate change (Schlesinger et al., 2000). It is therefore now accepted that among the assessments made of the impacts of changes in cropping pattern or other aspects of land use change carbon sequestration capacity is an important factor. The models developed to explain SOM dynamics have thus become essential tools for studies of carbon sequestration in soil. Nonetheless figures published for belowground carbon sequestration are seldom accurate, and this underlines, among other things, how limited our knowledge about SOM storage determinants and location remains (Schlesinger et al., 2000; Lal, 2001).

Beyond its role as a key compartment in nutrient cycles and as a regulator of climate change, SOM has also come to be valued for its influence on a wide range of so-called "ecosystem services" including those of water availability and quality, the erodibility of soil, and as a source of energy for soil biota acting as biological control agents of pest and diseases of plants, livestock and even humans (Swift et al., 2004).

6. Conclusion

The notion of an organic (i.e. life-related) component of soil is extremely ancient but before 1840, the role of soil organic matter in plant nutrition was uncertain and often controversial. Theories published by advocates of humus claiming material assimilation of SOM by plant roots were based on unverified facts and sometimes even on myths. At this time organic management was dominant and in that respect, agricultural practices tallied with scientific theory. During the early part of the subsequent mineralist period the pendulum swung completely and SOM management was excluded from mainstream theories on soil fertility and consequently from intensified cropping schemes. From 1940 onward however, clear evidence of the decline in soil properties linked to fertility in the field, scientific advances in agro-ecology, the stimulus provided by holistic philosophies concerning organic farming, and awareness of the environmental amenities provided by soil organic matter, have led to the promotion of SOM as a renewable resource and re-instated it as a target of management.

Over the past three centuries the passion for SOM can thus be described by a sine curve, both from the viewpoint of scientific concepts and that of field practices (Fig. 2). Agro-economic and environmental problems resulting from the mineralist and hygienic dogmas and the latest integrative advances in soil science, partly inspired by a holistic approach to the functioning of ecosystems, now support a SOM-centred vision of sustainable farming. During the few past decades the SOM-centred perception of the fertility of the plant–soil system has been partially rehabilitated, but on the basis of new concepts of the mechanisms involved. Early theories were wrong when defending the view that SOM was consumed directly by the plant (the heterophic hypothesis inherited from the Law of Return), but close to a truth when linking plant growth together with the "consumption" of SOM: ecological studies of soil suggest that SOM is a key factor in soil fertility due to its crucial position in biogeochemical cycles and, under the influence of the soil biota, both a sink and source for nutrients and energy for plant and soil organisms.

The history of the various soil organic matter concepts thus cannot be understood without linking it to changing fashions and ideologies, not only in science but also of spiritual and moral origin, a fluctuating economic context, and an ever more pressing human perception of environment. It is also one example among others of how fruitful it is for science to combine reductionist and holistic approaches. Furthermore, the rehabilitation and revision of the humus and SOM concepts respectively has greatly benefited from a continuous amplification of the scale at which it has been considered: first a local, soil-fertility related scale, later regional, and finally global (Fig. 2). The future will be built on the results of past understandings but also bring new challenges. For example the advent of biotechnology provides both the opportunity to advance soil biological management more rapidly, but at the same time it may resuscitate the prejudicial belief that services provided by SOM can be by-passed by technology.

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