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Soil fertility concepts over the past two centuries: the importance attributed to soil organic matter in developed and developing countries

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The theories about plant nutrition and soil fertility varied widely from the antiquity to the middle of the nineteenth century, with major (Thaer A. 1809. Grundsätze der rationellen Landwirtschaft (1809–1812). Berlin (Germany): Realschulbuch Ed.) or minor (Liebig J. 1840. Die organische Chemie in ihrer Anwendung auf Agrikultur und Physiologie. Braunschweig (Germany): Vieweg) importance attributed to soil humus or soil organic matter (SOM). The importance assigned to humus over the past two centuries will be developed in this historical paper. Intensification of agriculture in the twentieth century permitted an important increase in cultivated plant yield of food, fiber, wood, and biofuel production, not only in the northern countries, but also in some southern countries (e.g., India and China) with the emergence of the Green Revolution. However, the question of organic restitutions and the maintenance (or increase) of the SOM stock was, at times, not taken into consideration; consequently, there was a general decrease in SOM stock for many tropical soils. It is now widely accepted by scientists that SOM depletion is one of the major factors leading to degradation of ecosystem services and loss of ecosystem resilience: new alternatives are now necessary for the maintenance and/or increase in plant productivity and production of environmental services by agriculture. Therefore, this paper will also present some recent research in different tropical countries with a focus on agroecological management of tropical soils.

Keywords: soil fertility history; soil fertility concepts; soil organic matter; ecosystem services

Introduction

Today, the role of soil organic matter (SOM) in controlling the capacity of the world's 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

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and Craswell 1995; Wolf and Snyder 2003). The SOM contributes to a range of functions that can be connected to goods and services at the ecosystem level. Scientific recognition of the relationship among 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.

The objective of this paper is to present a brief history of the development of concepts and tools that recognized the interconnection among SOM, soil fertility, and ecosystem sustainability. In the process, distinction is made among three periods: the 'humic' (before 1840), the 'mineralist' (1840–1940), and the 'agroecological' (after 1940). Subsequently, we focus on some new alternatives proposed by the research systems for the development of sustainable agricultures in tropical countries and based on SOM management. The material presented draws heavily on Feller et al. (2006) and Manlay et al. (2007).

The humic period

The humic period may be conveniently divided into two distinct phases: the pre-nineteenth century debate and Thaer's humus theory.

The pre-nineteenth century debate

In ancient Greece and Rome, the concept of soil fertility referred to soil physical properties rather than chemical properties. Plants were assumed to be nourished by organic material of similar nature; 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 (Palissy 1880), is generally considered by historians of soil science to be a major forerunner of the mineral theory that was later established by Liebig. However, since Palissy's definition of 'salt' is not strictly mineral, this opinion is questionable (Feller et al. 2003; Feller 2007). In the seventeenth century, Van Helmont, among others, espoused Palissy's ideas about the role of soil as a simple source of water and mineral nutrients for the plant (Boulaine 1989).

During the eighteenth 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' (e.g., Valmont de Bomare, Pluche, Home, Duhamel du Monceau, La Salle de l'Etang, Bonnet, and Rozier, as mentioned in Feller and Boulaine 1987; Feller 1997a, 1997b).

Tull (1733) proposed a 'new agriculture' and fertilization practices based on soil tillage carried out as frequently as possible. This was based on the belief that since soil particles were a source of food for the plant, the structure of the soil had to be very finely divided to enhance uptake by roots. On the other hand, by the end of the eighteenth century, several authors – all cited in Bourde (1967) – for example, Priestley (1777), Fabbroni (1780), Ingen-Housz (1779), Senebier (1782), and de Saussure (1804), rejected these theories and experimentally demonstrated the gaseous origin of carbon during photosynthesis and the role of light. Contradictory debates arose on the subject, especially between Hassenfratz (1792a, 1792b) and Ingen-Housz. Without referring to experimental facts, Hassenfratz asserted that a fraction

of humus in the form of soluble carbon is directly assimilated by plants (carbon heterotrophy).

Thaer's humus theory

Thaer's '*Principles of Rational Agriculture*' (1809) integrated analysis of fertility management and the perception of sustainability. His treatise 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. 2003). For this reason, he deserves particular attention. His book was released during a period of controversy over the actual source of carbon used by plants, i.e., whether soil or atmosphere? Thaer did not deny that atmospheric CO_2 could be a carbon source for the plant, but since atmospheric CO_2 seemed unlimited, he considered SOM and its management to be the main limiting factor of plant carbon nutrition.

Unfortunately, Thaer derived his theoretical basis for plant nutrition from Hassenfratz's 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 Thaer, (1) most plant dry matter derives from the 'soil nutritive juices' contained in the fraction of SOM that is soluble in hot water (the remainder of the SOM is derived from CO_2 but is outside the farmer's control), 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 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.

Thaer'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°. This was 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. 2003). Thaer 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 this time). To optimize the economic value of this system, Thaer suggested that cash crop production could 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.

Thaer's analyses also included an economic appraisal of existing farming systems using the same range of cropping patterns. This analysis included all costs (labor, space, care of animals, etc.) of organic maintenance of fertility based on fallowing and manuring. One of his disciples, van Wulffen (1823, in de Wit 1974), while sticking to the systemic and organically centered approach, suggested that the use of Thaer's fertility index was not needed to quantitatively model farming sustainability and thus simplified the dynamic properties of Thaer's model for economic evaluations.

Conceptually, Thaer'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 agroeconomic sustainability of farming systems. His work seriously influenced the thinking of his peers during the first half of the nineteenth century. If Thaer had focused on mineral rather than organic budgets, he would probably have been regarded as the founder of Western scientific agriculture.

SOM: the mineralist period (1840s–1940s)

The end of the eighteenth 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 byproducts. A corresponding shift can be seen toward the middle of the nineteenth 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. However, this shift was not abrupt; these authors granted SOM an indirect role as a source of carbon dioxide during photosynthesis. In fact, in those days, many agricultural scientists shared a middle point of view and assigned a function in plant nutrition to both SOM and air.

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. Such ground-breaking work led to the conclusion that carbon comes from carbon dioxide, hydrogen from water, and other nutrients from solubilized salts in soil and water. However, it was evident that Liebig, who had a gift for synthesis, took much of his ideas from the work of Sprengel (1838, in van der Ploeg et al. 1999) and others. Since Liebig's findings 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 systems.

The *mineralist* theory was developed in a context of the challenge of growing urban populations located in areas increasingly remote from areas where crops were produced, and with increasing reliant on foreign food and fertilizer production (Hyams 1976). Agricultural scientists had therefore no difficulty adopting Sprengel and Liebig's ideas on '*mineralism*.' However, putting the theory into practice was hampered by the limited knowledge of phosphorus (P) and potassium (K) sorption and by some of Liebig's early assertions that later shown to be incorrect, e.g., the gaseous origin of the nitrogen (N) incorporated into the plant (Browne 1944; de Wit 1974); by contrast, Lawes, 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 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 by including 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 that time, the recycling of organic matter (OM) was 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 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 to enhance absorption of mineral, organic, or organo-mineral phyto-hormones is well recognized (Chen 1996; Chen et al. 2004).

Multifunctional concept of SOM

The 'mineralist' theory and the hygienic movement that arose from the 1880s onward, and which 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 systems during the Second Agricultural Revolution. However, knowledge about SOM underwent a significant breakthrough as early as the 1870s. Many studies contributed to better understanding of biogeochemical cycles and C and N mineralization, the role of SOM in exchange and sorption soil properties, aggregation (Manlay et al. 2007), and more generally as 'humus as an organic system' (Waksman 1938).

SOM: the ecological period (1940–2000)

Further scientific concepts of humus

The mineralist approach to the management of soil fertility reached its apogee in the 30-year period following the World War 1 with the establishment of high input, subsidized agriculture in Europe and North America. Chemical fertilizers underpinned the phenomenal 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). By contrast, the same time period saw a rise in a number of other scientific initiatives resulting in renewed and scientific and social interest in managing SOM under the rubric of 'sustainable agriculture.' These approaches can be seen as derived substantially from two convergent sources: (1) *developments in ecosystem science*, including improved scientific capacity for the

study of SOM and associated aspects of nutrient cycling, and (2) *concerns about environmental degradation* and the loss of ecosystem services, an important expression of which was the rise of the organic farming movement.

Societal criticisms concerning the sustainability of intensive farming arose as early as the 1930s, when the hypothesis, already expressed in the eighteenth and nineteenth centuries (Mårald 2002), began to be reformulated of a connection among 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 nineteenth century, and industrial synthesis of N and processing of P were mastered and commercially exploited by the early twentieth century. Agronomists at that 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 hygienic considerations that strongly limited the returns of nutrients from urban areas (Mårald 2002). Mineral fertilizers did not account for more than 15% of nutrients exported by crops in 1900 and, even in 1940, in the economic context of recession and world wars, still had only a limited contribution to the second agricultural revolution. Indeed N fertilization practices in Europe largely remained on low-cost biological fixation and the relatively high nutrient reserves of the soils (Boulaine 1989; Smil 1999; Mengel 2000).

During the first half of the twentieth century, intensification derived mainly from labor-saving inventions (e.g., motorization; Mazoyer and Roudart 1997). Erosion, usually the most spectacular, immediate and irreversible symptom of inappropriate 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. The agroeconomic cost of erosion 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 postwar 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 beginning of the oil crisis.

Humus and organic farming philosophy

Concerns about the impacts of high-input agriculture from the formal scientific sector may have been less important in triggering new interests in SOM management as a component of soil fertility than those that came from the development in 'alternative' farming practices under the rubric of 'organic agriculture.' Concerns about the connection between loss of biological function and decrease in the fertility of heavily cropped soils managed without organic practices date back to ancient times, but the lack of sound principles in soil ecology diminished the impact of these concerns on scientific thinking and land-use planners.

Steiner's lectures (1924) provided the foundation for *biodynamic agriculture*. The scientific basis of Steiner's lectures and publications of his disciples (e.g., Pfeiffer 1938) was weak, as they referred to both holistic and cosmogenic concepts (interrelations among stars, soil, and geochemical elements, plants, animals, and man) as the basis for a new kind of agriculture that excluded 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 common ethos of organic farming 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 humus at the heart of cropping sustainability: the 'Holistic Paradigm' and the 'Law of Return' (see Manlay et al. 2007).

In 'The Living Soil,' Balfour (1944) presented the quintessence of the philosophy of organic farming. Her leading hypothesis was that, according to her criteria, the reason for the obvious 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 perceived '*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 concept is best illustrated by the biotic pyramid of Albrecht (1975, cited in Merrill 1983). This pyramid is made of several layers, with soil as the base and man at the top of the pyramid. Howard's opinion, as expressed in his '*The Soil and Health*' (1952), matches Balfour's holism notion. His more precise causal interpretation of the relation among 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 celebrated technical handbooks for the production of compost, which he termed 'manufactured humus.'

Toward 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 substantial efforts to find sustainable means of agricultural production (Conway and Barbier 1990). This focus naturally centered on the use of renewable natural resources. In the case of soil fertility management, this resulted in fresh attention to the management of OM 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 OM (crop residues, compost, or manure) 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 at the turn of the twentieth century (Mokwunye and Hammond 1992; Palm et al. 1997), and maintenance and/or improvement of the SOM status is central to its philosophy. The 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 N-fixing bacteria (Giller 2001) have still to be matched in other groups.

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). This had 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 that were founded as early as 1939 (Haughley Research Trust in UK, by Balfour), 1945 (Rodale Institute in the USA), 1950 (Germany), or the mid-1970s (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 worldwide 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 SOM management for the definition of sustainable cropping patterns; such systems were generally widespread before the mineralist era but 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 that were derived empirically from observation of nature, many of which have been retained in traditional indigenous knowledge in various parts of the world. This progress has been documented recently in a book (McNeely and Scherr 2002) that celebrates the achievement of what they term 'ecological agriculture.'

Within the scope of global change related to man-induced release of greenhouse gasses (GHGs) in the atmosphere, global carbon (C) transfers from and to the soil have been receiving increasing attention for more than a decade (Schlesinger et al. 2000). The C pool in the world's soils is three times that in the atmosphere (IPCC 2000). Any change in the below-ground pools resulting from changes in land use (conversion to crop or pasture, afforestation) will thus have a great impact on C concentration in the atmosphere. Most C flows are mediated by SOM, hence the numerous studies on the soil C oxidation: fixation balance related to land use and climate change undertaken at the plot scale, but in the framework of global issues (Schlesinger et al. 2000). New cropping patterns will be appraised for their C sequestration capacity.

Beyond its role in the regulation of global climate change, as well as that as a key compartment in nutrient cycles, SOM has also come to be valued for its influence on a wide range of so-called 'ecosystem services,' in the sense of the Millennium Ecosystem Assessment (Hassans et al. 2005; MEA 2005), e.g., food production, nutrient cycling, water management, climate protection/regulation, energy, biodiversity preservation, transformation and dynamics, landscape management, and cultural services. Such services also include water availability and quality, erodibility of soil, and SOM as a source of energy for soil biota, acting as biological control agents of pest and diseases of plants, livestock, and even humans.

Tropical soil management: ecosystem services

This section is mainly based on Ganry et al. (2001, 2005) and Feller et al. (2010). It focuses on SOM management and ecosystem services for tropical soils and conflicts for SOM among soil, livestock, and energy in the tropics. Through interactions among the different compartments of the ecosystem (soil, atmosphere, hydrosphere, biosphere), the soil impacts many ecosystem services that are relevant at local

(farmer level) as well as global scales (society level). For most of these soil services, organic restitutions (ORs) and SOM play a major role through their impacts on soil fertility (physical, chemical, and biological soil properties) – the local scale and farmer perception – and C sequestration – the global scale and society perception.

Since OR and SOM are easily expressed in the form of organic C and soil organic C (SOC), C management in soils is a major strategy for both developed (mainly northern) and developing (mainly southern) countries, even if the hierarchy of services is not always the same (e.g., excessive use of nutrients for plants in the North and depletion in the South, and competition for management of organic residues in southern countries among soil fertility, animal feeding, and/or energy production and not in northern ones; Lal 2006). However, many soil degradation problems remain similar such as excessive runoff, accelerated erosion, dam embankment, biodiversity preservation, decline in soil biological activity, and need for atmospheric C sequestration.

OM management

There is urgency and a serious concern to feed the world's growing population of 6.7 billion in 2009 and expected to be 7.5, 9.4, and 10 billion by 2020, 2050, and 2100, respectively. With reference to managing the SOM pool, there are important features of the projected rapid increase in world population: (i) almost all of the future increase in population will occur in developing countries (Cohen 2003) where the soil and water resources are already under great stress, and (ii) such an increase in developing countries is unprecedented and it does not provide enough time to make appropriate adjustments to meet the demands of such expanding populations.

There are about 1020 million food-insecure people in the world (FAO 2000; Sanchez 2002; Rosegrant and Cline 2003; Borlaug 2007), and the number may increase by another 100 million by 2015. An additional 3.4 billion people suffer from hidden hunger because of the intake of food grown on poor quality soils (UN 2006). Globally, food production must be doubled by 2050 to meet the increasing demand of the growing world population. Management of SOM pool can play an important role in advancing food security (Lal 2004). There are implications of diet and nutrient requirements on soil quality (Lampert 2003), for which judicious management of SOM is crucial.

While the data on crop performance in relation to some recommended management practices are evident in developing countries, from ancient and recent studies (Siband 1974; Pieri 1992; Ganry et al. 2001), especially for sub-Saharan Africa, credible information is needed on the rate of OM storage for diverse soils and ecosystems. Research data are also needed with regard to the soil-specific functions relating SOM storage to soil quality parameters (e.g., available water-holding capacity, structural stability, erodibility, water and nutrient-use efficiency, water transmission properties, aeration and gaseous diffusion, emission of GHG, including CH_4 and N_2O, and agronomic/biomass yields).

Low agronomic productivity of soils in developing countries is partly attributed to human-induced soil degradation and the attendant decline in soil quality (Lal 2004). There is a strong link between soil quality and agronomic productivity on one hand, and SOM (or SOC) and soil quality on the other. Numerous positive correlations exist between SOC content and many soil properties involved in fertility for tropical and subtropical areas (Feller 1995a, 1995b; Lal 2006). Extractive

practices widely used by resource-poor farmers in developing countries deplete the SOM pool, degrade soil quality, and adversely affect agronomic productivity. Thus, agricultural sustainability is contingent upon land-use and management systems that enhance and maintain high levels of SOM pool.

A review of available data on relationships between SOC content and annual yields was published by Lal (2006) for tropical soils. Based on these data, it was calculated that increase of SOC pool by 0.5 Mg C ha^{-1} $year^{-1}$ in the soil can increase grain production of 2.1% per year. With an increasing SOC pool by 1 Mg ha^{-1} $year^{-1}$ food production may increase by 9–12 million Mg in sub-Saharan Africa and 24–40 million Mg in all developing countries. Improving soil quality, and increasing SOM along with the inputs required to raise productivity, remains a major challenge (Lal 2009).

Many agricultural alternatives theoretically exist for such increases in both plant productivity and SOC content. Ganry et al. (2001) comment on such alternatives for annual cropping systems in semiarid Africa: (1) parkland systems as cultivated parkland, sheanut parkland, *Faidherbia albida* plantings, etc.; (2) diverse agroforestry systems; (3) mulch-based systems as improved (herbaceous or tree) fallows, alley cropping, cover crops with no-till systems; and (4) compost and manure applications. For other tropical regions, afforestation, conservation agriculture systems (mulch and no-till based), and no-burning sugarcane systems are widespread, especially in Latin America. Examples of the latter systems will be described in relation to two ecosystem services: soil carbon sequestration and soil biodiversity.

Carbon sequestration, tillage, and cover crops

In soils' literature, the term 'carbon sequestration' is often used in the same sense that C storage. Bernoux et al. (2006) emphasized the necessity to distinguish these two concepts and proposed the following definition for the concept of 'soil C sequestration': '"Soil–plant carbon sequestration" for a specific agroecosystem, in comparison with a reference, 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 (taking into consideration the global warming potential of the different GHGs involved) computing all emission sources at the soil–plant–atmosphere interface, but also all the indirect fluxes (gasoline, enteric emissions, and so on).'

Thus, establishing a C sequestration balance must take into consideration the sum of the balance of all the GHGs (CO_2, CH_4, N_2O), considering only the GHG fluxes between soil and atmosphere. This point specifically addresses the need to consider the C transfers into other parts of the landscape in a solid (erosion) or soluble (runoff or lixiviation) form. If C–CO_2 fluxes at annual or decennial scales are generally estimated by soil C storage during the time span considered, estimations of CH_4 and N_2O fluxes need measurement at the very short time span of daily and weekly scales.

The importance of soil CH_4 and N_2O fluxes for a right soil C sequestration balance is well known. Six et al. (2002) published a review of N_2O fluxes for agricultural soils under no tillage (NT) systems in temperate regions. About 50% of the cases under NT emitted much more N_2O than the conventional plots, sometimes at a level enough to compensate the beneficial effect of SOC storage by the same system. But no data were available at this time for tropical regions. Under tropical

agroforestry systems involving ORs from tree legumes, data published by Millar and Baggs (2004) and Millar et al. (2004) show that risks of high rate N_2O emissions in such systems are high, depending on the level and organic N content of the restitutions. Data given below consider these different aspects for two types of Brazilian agrosystems: NT and plant cover and sugarcane systems.

NT and cover-plant systems (Brazil and Madagascar)

Direct seeding mulch-based cropping or NT systems with two crops per year without soil tillage have widely been adopted over the last 10–15 years in the Cerrados (central region with wooded savannah) of Brazil. They are replacing the traditional soybean mono-cropping with fallow under conventional tillage (CT). Variation in SOC stocks (on a mass equivalent basis for the 0–40 cm layer) was studied for a 13-year chronosequence (NT1 to NT13) in the Cerrados near the city of Rio Verde city (with a clayey Oxisol). The average SOC increase taking into account a 'baseline correction' (variations in clay content, and initial SOC content) was estimated at 1.26 Mg C ha^{-1} $year^{-1}$. This range of value was confirmed by computing the SOC dynamics with the G'DAY model (Corbeels et al. 2006) for the same plots.

Measurements of N_2O fluxes were not conducted exactly on the same location, but in the same region and under the same climate and the same soil type, near the city of Goiania (Metay et al. 2007). Two 5-year-old systems, tillage (disk on the first 15 cm called offset: OFF) and a direct-sowing, mulch-based crop system (NT) with an additional cover crop, were studied during a cropping cycle. The SOC storage by NT corresponded to 0.35 Mg C ha^{-1} $year^{-1}$. Both N_2O and CH_4 fluxes at the soil surface were determined using the close-chamber technique. No significant differences between treatments were observed for either gas.

Total annual estimated emissions of N_2O range from 31 to 35 g N_2O–N ha^{-1} $year^{-1}$ for NT and OFF, respectively, which is low and corresponds only to 0.03% of the total N fertilizer applied. The CH_4 fluxes were very low as well: both treatments act as a source of CH_4 (245 and 403 g CH_4–C ha^{-1} $year^{-1}$ for NT and OFF, respectively). On a CO_2–C equivalent basis, these results correspond to 4.1 and 4.7 kg CO_2–C ha^{-1} $year^{-1}$ for N_2O and to 1.9 and 3.1 kg CO_2–C ha^{-1} $year^{-1}$ for CH_4 for NT and OFF, respectively. As a result, the C sequestration balance, taking into account the CO_2, CH_4, and N_2O on a CO_2–C equivalent basis, is positive for the values determined for N_2O, and CH_4 fluxes are very low. Similar results (for SOC storage and N_2O flux) were obtained in Madagascar for a clayey Oxisol under NT system (Rabenarivo et al. 2009).

Sugarcane systems (Brazil)

Another example of a complete balance (Cerri et al. 2004) is the case of an alternative management strategy for sugarcane (*Saccharum officinarum*) production in Brazil (São Paulo state) for a 3-year system. In Brazil, sugarcane covers almost 5 million hectares (Mha) and the process nearly always involves a pre-harvest burn. There is, therefore, a near complete combustion of leaves, and consequently a transformation of plant C into CO_2, accompanied by emissions of N_2O (transformation of part of the plant into N_2) and CH_4. An alternative to this mode of management is not to burn sugarcane before harvesting. This alternative is set to become law in São Paulo state.

First results indicate that the adoption of 'without burning' (WB) management is accompanied (during the first years) by an increase in soil C storage and a decrease in CH_4 emissions. Moreover, adopting harvesting without burning has other positive effects, for example, an increase in the quantity and biodiversity of soil macrofauna (see below). In addition, a decrease in nutrient losses and a reduction in the risk of erosion are also observed. However, a WB management strategy involves mechanized harvesting and can have socioeconomic implications. In terms of C input to soil, WB management represents a restitution of $\approx$ 13 Mg of dry matter per year, or about 5–713 Mg C per year.

The final annual balance of the two systems shows that the WB management strategy is a win-win option: the soil C increases of 1625 kg C ha^{-1} $year^{-1}$ and the net emissions of N_2O and CH_4 on a C–CO_2 equivalent basis are reduced (209 and 3 kg C eq. ha^{-1} $year^{-1}$ for CH_4 and N_2O, respectively), resulting in a benefit of 1837 kg C eq. ha^{-1} $year^{-1}$. Nevertheless, this study represents an isolated evaluation that needs to be confirmed. In addition, this study was carried out within a productive cycle of sugarcane and therefore did not include the effects of the replanting (which occurs every 6 years) on soil C dynamics.

Soil biodiversity

NT and cover-plant systems (Brazil)

The example concerns the same situations described above for a 13-year chronosequence. Changes in land-use management often lead to changes in soil macrofauna. Soil disturbance generally has a negative effect on invertebrate populations due to direct mechanical damage by the equipment, and indirectly through loss of SOM and changes in soil structure and water regime (Chan 2001). These modifications, in turn, affect soil C dynamics and many other soil properties. In this experiment, soil macrofauna were hand-sorted from soil monoliths (30-cm depth, TSBF (Tropical Soil Biology and Fertility Programme) method (Anderson and Ingram 1993). Compared to natural vegetation, soil macrofauna in cultivated soils was strongly modified. In CT, biomass and density were low, being considerably less than in NT systems. With increasing age of NT (at NT11), total macrofauna density decreased due to decrease in termite and ant densities despite increase in earthworm density. Conversely, total macrofauna biomass increased due to a strong increase in *Coleoptera* larvae biomass.

As reported in other studies, the biomass, density, and diversity of soil macrofauna are greatly improved in NT compared to conventionally tilled systems. This can strongly modify the soil functioning, especially soil C storage (Martin 1991). The only significant differences between NT (as a whole) and CT systems were measured for earthworms and *Coleoptera* density and for *Coleoptera* biomass. At the present study sites, as well as at other sites from Brazil (Brown et al. 2001, unpublished data), *Coleoptera* were mainly scarab beetle larvae (white grubs). It appears that some white grub species can be rhizophagous (pests like *Phyllophaga*); some species can be beneficial saprophagous or coprophagous (*Cyclocephala*), and some species can be intermediate (*Diloboderus*). But the high abundance of white grubs with no impact on root damage and plant production suggests that most of the white grubs are saprophagous. These animals ingest SOM (especially residues) and mix it with soil mineral particles, excrete stable casts, and create burrows. This activity can lead to the creation of 'hot-spots' of soil enrichment in the upper

20–30 cm of soil, with significant increases in P and SOM contents. As activities of white grubs are close to those of earthworms, these grubs should be considered among the soil engineers (Lavelle et al. 1997). Earthworms are known to affect the dynamics of SOM in the long term through the physical protection of OM in their casts (Martin 1991).

In conclusion, compared to conventional systems, direct seeding and mulch-based systems provide an ideal environment for the re-establishment of soil engineer (earthworms, white grubs), litter engineer (termites, ants, millipedes), and predator (spiders, centipedes) populations, thus leading to a higher biological activity and regulation in NT systems. This high activity associated with the high abundance of soil and litter engineers, the presence of abundant crop residues and the absence of mechanical tillage can explain the increase in soil C stocks measured in NT systems. Additional research is needed to relate soil C storage with the activity of soil macrofauna and especially of white grubs whose beneficial activity needs to be confirmed or refuted.

Sugarcane systems (Brazil)

This example concerns the same situation described earlier for a 3-year, non-burnt sugarcane plantation (Cerri et al. 2004). Results are quite similar to those of NT systems: (i) a large decrease of density and biomass of soil macrofauna after deforestation and 50 years of (conventional) burnt treatment, and more than 75% of individuals are *Coleoptera* larvae, very often a parasitic animal for sugarcane; and (ii) only 3 years of non-burnt treatment, resulting in a important mulch on the soil surface, allow a very large increase (multiply by about 7) of density and biomass to the main benefit of earthworms and ants (Cerri et al. 2004).

Reconciling SOM uses

This section is largely based on a part of the Lal's (2006) paper and emphasizes the absolute need to improve SOC stocks for emergence of sustainable agroecosystems for tropical and subtropical areas. However, the retention of crop residues and use of compost, animal manure, and other biosolids on agricultural soils can happen only if alternative sources for competing uses of such materials (for fodder, fuel, construction, etc.) are identified and made available. Under the prevailing socio-economic and policy environments, practices such as NT, agroforestry, diversified/mixed farming systems, precision farming, and judicious use of these options do not meet the social and economic needs that determine farmers' behavior.

Therefore, there is a need for a radical change in mindset at all levels of the societal hierarchy. There must be a drastic paradigm shift so that soil resources are not taken for granted. It is important that sustainable management of soil resources (through NT farming, retention of crop residue as mulch, and use of manure and compost to enhance soil fertility) is an integral component of any government program related to improving agricultural productivity, achieving food security, enhancing water quality, and mitigating climate change. Now is the time for this important action.

There are two principal factors throughout the developing world in the tropics and subtropics that are the driving forces responsible for depletion of the SOC pool leading to degradation of soil, pollution of water, and emission of GHGs and

particulate material into the air. These are: (i) the removal of crop residue for use as fodder for cattle followed by intensive grazing as commonly practiced in South Asia and (ii) the use of animal dung as household fuel for cooking. Consequently, soil nutrient balance is negative, the SOC pool is depleted, soils are prone to crusting and compaction, because of a decline in soil structure, and are subject to severe erosion by wind and water due to bare, unprotected surfaces and high erodibility. These degradation processes reduce agronomic/biomass productivity, decrease response to inputs such as fertilizers and irrigation, and require additional labor (plowing) to prepare a desirable seedbed/tilth. In addition to reduced production, there are serious problems of soil degradation, water pollution, and decline in air quality.

Lack of a suitable fuel for household cooking is another factor driving the complex process of soil and environmental degradation. Rather than using it as a soil amendment, animal dung is often used as a cooking fuel in developing countries of Asia and Africa. In addition to being a serious health hazard to young mothers and the children with them, not returning the dung to the soil disrupts the nutrient cycling, accelerates the depletion of SOM and plant nutrients, reduces agronomic/ biomass productivity, and jeopardizes sustainability of the specific land-use system.

Such extractive systems were sustainable practices for millennia in ancient countries such as India and were ecologically compatible as long as the population was low, the land:people ratio was high, and the demands on natural resources were low. With high demographic pressures, a low land:population ratio, and high demands for natural resources that have been severely stressed, these extractive practices are causing severe environmental degradation. The reversal of this degradation process requires a paradigm shift in traditional systems of using natural resources. Livestock management, an important component of any agrarian society, must be based on viable forage-based rotations and sound pastoral systems. There is a strong need to develop judicious fodder production system through incorporation of forages within the rotation cycle so that soil quality and SOM contents are enhanced.

The system of removing residues from cropland to feed cattle must be carefully assessed. Similarly, development/identification of clean sources of household fuel is essential to reducing risks to the health of women and children, and making it possible to use dung/compost as a soil amendment. Establishment of biofuel plantations, for example, with crops such as *Prosopis* (mesquite), *Jatropha* and *Leucaena* on areas such as degraded/wastelands and village common land, may be useful to restoring degraded soils and ecosystems, improving the SOC pool, enhancing the environment, and improving the standard of living. However, feasibility of growing biofuels must be objectively assessed for local and site-specific conditions.

Conclusions

There is a long history of scientists' engagement in the study of SOM, SOC, or the C cycle as a consequence of their conviction of its functional value. There are many cases, often forgotten, of perceptions that predate present-day concepts that are accepted as essential for sound management of natural resources such as that of sustainability (e.g., Thaer and his system of prediction of the sustainability of a farming system). Moreover, these ideas have often been based on the development of new approaches (such as modeling) and tools (such as Free-Air Carbon dioxide Enrichment-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 in 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, with 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.

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