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«Humus, fertility and sustainability of cropping systems: concepts over the past three centuries»

by

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FOREWORD

With the agreement of both authors I have introduced this paper into our publications list in order to have access to these concepts as well as their evolution along the last three centuries, having in mind a better understanding for agriculture and forestry practitioners.

More basicl knowledge over the nature of soils was my main concern. My comments are related to what is already known but pushed aside in favor of plant productivity for more market demand. Feller and Manlay have described the slow evolution of soil knowledge over three centuries and the unremitting deviation of knowledge for plant and animal productivity. Without any doubt the authors have brought to light large parts of fundamental knowledge on soils we did not care about during the last century. They have tackled apprehensively soil energy by some reference to thermodynamic out of equilibrium. On the other hand there is no reference to biochemistry related to humus formation since biochemistry of polyphenols and polymers, namely lignins.

My first attempt using RCW and the way it performs since 20 years have raised among the scientific community some low profile questions, but no real curiosity about the way evolution is keeping on. The evolution of RCW on soil pedogenetics have shown large similarities under tropical climate as temperate. Still no questions were raised over the basics of humus formation mechanisms.

From the beginning this question of pedogenesis was of some concern to me, and with colleagues we began searching for recent developments through biochemistry, biology and physics. We were shocked by finding no clues but some promotion of composting a technology known from the Kings of the ancient Egypt, still highly praised in "modern" agriculture and forestry, even "glorified" as a progress…….of *Homo erectus!*

This paper gives an historical perspective and shows clearly how humus was perceived throughout centuries but with no relation to its structure and performing mechanisms, but only focusing on plant production for man and related animals. The "agronomical" perception of humus is still highly related to Liebig's approach in 1840 and Schleusing later on, while general chemistry knowledge was booming. Feller and Manlay are also concerned by he forest soils. Humus classification first put forward by Hundeshagen has by no means contributed to better understand soil origins, their different types and their raison d'etre. Later on many other authors paid attention to is question, such as Wiilde, Kubiana, Duchaufour, etc. but they all dealt with soil classification on pedogenetic basis, chemical or physical. From what we know, no one as seen and understood **HUMUS AS AN ECOSYSTEM OF ITS OWN WHITHIN THE UNIVERSAL BIOLOGICAL, CHEMICHAL AND PHYSICAL RULES**. Even he most recent publications regarding agricultural and forest soils are using he term ORGANIC MATTER or SOM (Soil Organic Matter) we see throughout the agronomic and forestry literature for close to two centuries. This WORD ORGANIC MATTER, shows how ignorant we are over the fundamentals of humus and its quadruple: physical, energetic, biochemical and biological composition and dynamics.

On many respects this humic system is similar to aquatics with regard to its dynamic but to the mobility of its biological components, thermal and nutrient regulation. Energy is brought from detrital origin which also contribute to physical soil structure. This detrital source is characterized by a large polyphenolic polymers content where lignins are the main source. In fact, this humic model represents he very base of pedogenesis and sustainability in agriculture, since nothing is more permanent than a forest ecosystem responsible for productivity and biological dynamic within a broad biodiversity scope.

All attempt for describing humus in static terms makes no sense, even if is a path privileged by most authors as stated by Feller and Manly. This paper clearly shows why this static approach was and still favoured. Most authors follow the same path: they describe and classify soils and switch to plant nutrition, with emphasis on nitrogen and phosphorus. Earlier, carbon was the main source of concern but at very different scale than today's.

Solutions put forward are always the same, most of the time, fertility being the center of the question, but without any relation to soil structure dynamics where humus evolution blaze he trail. Consequently, this plant nutrition approach calls for strict artificial interventions as we know them for over a century. In order to prevent this "one track approach" people from Germany and UK have put forward an ORGANIC AGRICULTURE concept, supposing there could be an other type of agriculture. This was a characteristic romantic reaction refusing to acquire new knowledge as medicine for example for a long period of time. Even today, microbiology see his field of interest through the scope of diseases while being the most important element and regulating the life on earth.

Not recognizing the basic humus evolution mechanisms and promoting the value of carbon sinks in order to control he greenhouse effect by carbon dioxide is certainly a fact of our good old human nature. Therefore, we can seep under the rug large parts of our knowledge and refusing to recognize the importance o pedogenesis and all of its universal ruling mechanisms allover the world.

Professeur Gilles Lemieux

Humus, fertility and sustainability of cropping systems: concepts over the past three centuries

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"As the man became civilized he failed to recognize that the world was given to him for usufruct alone, not for his consumption, and still less for profligate waste. Erosion is one form of toll that man is paying for his extravagance. The extent of the penalty did not become evident until the last of agricultural frontiers began to feel the effects of accelerated soil wastage." (Bennett, 1939)

Introduction

(106-43 B.C.), "humus" in the sense of "soil" progressively

Land degradation is a man-induced process that affects all the components of ecosystems: soil, plant, animal, hydrosphere, and atmosphere. Soil degradation for instance, the "deterioration over time of key soil attributes required for plant growth or for providing environmental services", is said to affect 40% of the world's agricultural land and is already responsible for a decrease in crop yield on 16% of this land (WRI, 2000). Whether soil resources should be seen as renewable is questionable; nevertheless, the decline of civilization has often been interpreted by archeologists as a consequence of the depletion of soil resources that brought human societies to the limit of sustainability (Olson, 1981).

The role of soil organic matter – SOM or humus – in controlling the aptitude of soil resources to deliver agricultural and environmental services on a sustainable basis and at both local – e.g. fertility maintenance – and global – mitigation of atmospheric carbon emissions - scales is well established today (Tiessen et al., 1994; Syers and Craswell, 1995). There is thus a particular relationship between concepts concerning humus, fertility and sustainability. However scientific recognition of this relationship and its implications for the definition of farming practices have fluctuated over time, partly due to the difficulty in adequately defining the three concepts.

This work reviews changes in the concept of humus in relation with those of fertility and sustainability. Written from a historical perspective, it first describes the changes in the definition of the concept of "humus" and then relates the relationships between the three concepts in both agricultural sciences and farming practices. It is mainly concerned with history over the last three centuries. Three periods have been distinguished: "the humic period" (before 1840), the “mineralist period” (1840-1940), and the “environmentalist period” (from 1940 up to the present time).

A review of the various historical meanings of humus (Feller and Boulaine, 1987; Feller, 1997a)

The etymology of humus is Latin. Up until now, the word “humus” has been used to describe three different concepts: humus as a horizon, humus as a chemical constituent and sometimes humus as a principle.

To Roman writers (Vergil, Pliny the Elder and Columella), "humus" meant “soil” or “earth”. Thus, Vergil named loamy soil “pinguis humus” and used the words “humus”, “solum” or “terra” interchangeably to convey the notion of soil or earth. At the beginning of the 1st century, after Cicero died out and was replaced by "terra"(Martin, 1941).

"Humus" probably re-entered European scientific vocabulary in the 18th century. According to various French dictionaries it reappeared in the Diderot and d'Alembert's Encyclopaedia (1765, vol.8), with the meaning “mould, garden earth, earth formed by plant decomposition. It refers to the brown or darkish earth on the surface of the ground. Refers to mould or vegetable mould" (translated from French). However, the term “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 different volumes of the “Cours d’Agriculture” by Rozier (1781-1805), but surprisingly 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 instance:

..."to produce mould or humus, the only vegetable mould" (vol. 1, 506),..."a soil which lacks only humus, mould or soluble earth, ... is the only vegetative earth. The other earths serve solely as matrices for plants" (vol .1, 568),..." calcareous earth is thus the only vegetable mould, the perfect humus that is soluble in water, and the only one to establish and constitute a "frame" for plants... if plants are piled up... and undergo decomposition... we will end up with a pure calcareous earth, the perfect humus. Farmers, keep on producing this precious humus, which is real "animal earth", the only one present in their composition (the plants)..." (vol. 9, 390-401).

For Patrin (1803), “humus” referred to "soil": "it is the outermost layer of the earth... from which the soil is formed when the rock is not uncovered... its depth varies from two or three inches to several feet..."; 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".

1.1 The “humus-constituent” concept

The “humus-constituent” concept first appeared in 1809 when it was used by Thaër, in his "Rational principles of agriculture", which was first published in German (1809) then in French (1811), and this was probably the first time Thaër used the word "humus" to mean soil component:

"The usual name for this substance is mould. This designation has been widely misunderstood as it referred to the layer of vegetable earth rather than a particular part of the substances that form earth . This mistake has been repeated even in the writings of eminent agronomists and has led to increasing misconception of this part of science. This is the reason why I have adopted the term humus, which is unequivocal. Generally, the scientific designation ‘earth’ is not appropriate; properly speaking, it is not earth; it was only designated as such due to its powdery form... "Humus is the remains of animal and plant putrefaction, it is a black body..." (translated from French).

1.2 The “humus-horizon” concept

The ”humus-horizon” concept appeared very early (see above) 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. In the class "Earths" (terrae), he described the order "Dust Earths" (Terrae macrae), the genus "Loam or mould" (or Humus) and distinguished seven species.

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 who, in his noteworthy works (1879; 1884), laid the foundations for the present day scientific studies on the different forms of humus, as well as a general survey of soil genetic processes in cold and temperate climates. His book, "The natural forms of humus" (1889), which in French included the previously cited works, is a treatise on the changes of brown soils to podzols; its distinction of different types of humus horizon can still be considered valid today.

“I propose to name the two principal types ... of humus ... from beech forest "Mull" (mould) and "Torf" (peat)”: in Danish, "muld" and "mor" for Mull and Torf, respectively.

This is followed by a very detailed description of the soil profile, a microscopy study, a number of mechanical and chemical analyses, and a comprehensive study (pp. 20-28) on the litter decomposing organisms, mycelia and earthworms, with quantitative data. Transient formations - mould-peat (mullartiger Torf) - are then described (pp. 45-64); they seldom contain earthworms but instead numerous insects and mycelia. 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".

As far as uncultivated soils are concerned, Müller's study opened up the era of biological Soil Science. The word “Humology” was even proposed by Hamor in 1929 in place of Soil Science (quoted by Waksman, 1936). 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).

1.3 The “humus-principle” concept

The soil biota (plant, fauna and micro-organisms) has an important place in the ”humus-horizon” concept. When applied to agriculture, the conceptual association between humus and life is a determining aspect of organic farming theories. Rusch’s “Soil Fertility” ("Bodenfruchtbarkeit", 1972) exposes a more holistic and philosophic perception of humus as a basis for certain conceptual theories of organic farming. According to Rusch, humus “is the concept of the original force of our forefathers... it 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 (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... with a tissual liquid filled with anions and cations. It is only this that ought to be called Humus insofar as it is a substance. It can be said that Humus is the one primitive tissue that exists, the one on which the plant lives”. And Rusch concludes: “In short, Humus is a principle, an original force, the driving force behind fertility”.

The humic period (before 1840)

1.4 The ante-Thaër debate

In Ancient Greece and Rome, soil fertility referred to its physical rather than chemical properties. Plants were assumed to feed on organic material of similar nature; for instance, olive stones were brought to olive trees, and vine shoots to vines. 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., 2001). 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” 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, at the end of the 18th century several authors for example Fabbroni (1780, cited in Bourde, 1967), Priestley (1777), Ingen-Housz (1780, in Bourde, 1967), Senebier (1782 in Bourde, 1967) and de Saussure (1804) denied 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). In fact, in those days, many agricultural scientists shared an intermediary point of view and assigned a function in plant nutrition to both humus and air. For instance, Martin (1829), and Boussingault (1838, cited by Grandeau, 1879, reference not given) granted humus an indirect role as a source of carbon dioxide during photosynthesis.

1.5 Thaër's theory of humus, integrated analysis of fertility management and the perception of sustainability (1809)

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 in the definition of sustainable cropping practices. For this reason, Thaër's work has received particular attention in this paper.

Theoretical basis

Thaër's book was released during a period of controversy whether soil or atmosphere was the actual source of carbon used by plants. Unfortunately, Thaër derived his theoretical basis for plant nutrition from Hassenfratz' ideas (1792a; 1792b) rather than from the works of de Saussure's (1804) (to which he refers in the sense which best fits his theory). According to Thaër: (1) all plant dry matter derives from the "soil nutritive juices" contained in the fraction of soil humus that is soluble in hot water; (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 fertility.

An integrated tool for the analysis of humus-based management of agro-systems fertility

Thaër's main qualities were the precision of his definitions and his effort to quantify certain principles of rational agriculture from bibliographic and experimental sources. He created an analytical tool based on a fertility index ranging from 0-100 computed from an empirical function of soil texture (that distinguished 20 soil types), organic fertilization (fallowing and manuring intensities), crop species and yield (Feller et al., 2001). Thaër simulated the evolution of his fertility index for several cropping systems, and was thus able to rank them with regard to their agricultural sustainability.

An example of such a simulation is provided for two cropping systems in **Erreur ! Source du renvoi introuvable.** (see the footnotes of **Erreur ! Source du renvoi introuvable.** for computation details). The first traditional triennial rotation leads to a net fecundity loss of 17°. Thaër concludes that this system will not maintain the soil fertility capital beyond the sixth year of cropping, unless the field is manured after the fifth crop. A second improvement rotation results in a gain in soil fecundity (+30.5°). To optimize the economic value of this system, Thaër suggests that cash crop production be substituted for some forage production, which would keep the soil fecundity level at its initial value. This is certainly the first example of real concern with farming sustainability, and what is more, it is based on organic practices.

His analyses also included an economic appraisal of existing farming systems using such cropping patterns. It included all the costs (labor, space, care of animals) of 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. After all, he tackled modern agricultural issues such as the identification of soil quality indicators, systemic analysis and farming agro-economic sustainability. His work seriously influenced the thinking of his peers during the first half of the 19th century. If only Thaër had focused on mineral rather than organic budgets, he would probably have been regarded as the founder of Western scientific agriculture.

Humus in the mineralist period (1840's-1940's)

In the middle of the 18th century a shift in the scientific conception of the role of humus in plant nutrition can be seen in the works of Martin (1829) and Boussingault (1838, cited by Grandeau, 1879, reference not given). Martin claims that most plant carbon stems from air and water, but grants humus a major role in plant carbon nutrition, as a precursor of carbon dioxide in the atmosphere.

1.6 Liebig's mineral nutrition theory

Liebig, in his authoritative "Die organische Chemie in ihrer Anwendung auf Agrikultur und Physiologie" (1840), definitively established by means of scientific experiments that the origin of plant dry matter is mineral compounds: carbon comes from carbon dioxide, hydrogen from water, nitrogen and other nutrients from solubilized salts in soil and water. Since Liebig's findings accounted satisfactorily for the fertilizing effect of mineral inputs, they provided the basis of modern agricultural sciences. Liebig promoted the use of mineral fertilizers to compensate for soil mineral depletion and his work paved the way for recommendations for the massive use of chemical fertilization in cropping patterns.

Although agriculturists had no difficulty adopting Liebig's viewpoint on "mineralism", the sustainability of mineral fertilization alone was debated very soon after Liebig's ideas became widely known. Ville (1867) certainly expressed one of the most optimistic opinions about the viability of inorganic fertilization. Grandeau (1878) on the other hand, warned against Ville's assertions. As an advocate of mixed fertilization, he suggested that humus was vital for plant growth, since it increased the solubilization of mineral nutrients and thus their bioavailability to plants – a new concept. Liebig sent Grandeau a congratulatory letter expressing full agreement with Grandeau's theory. 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 already emphasized the low economic cost of organic fertilizers produced on the farm. In fact, the limited references to chemical fertilizers in Gasparin's textbook is certainly due to the limited production and use of inorganic fertilizers before the 1880's (Boulaine, 1989).

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).

1.7 The growing gap between farming practices and advances in knowledge about humus

However strong the influence of the "mineralist" theory may have been on the definition of new organic-free cropping patterns during the second Agricultural Revolution, knowledge about humus underwent a significant breakthrough as early as the 1870's.

Biogeochemical cycles and C and N mineralization

Ingen-Housz (1794; 1796) was probably the first to measure SOM mineralization through CO_2 emission, followed by Boussingault and Levy (1852; 1853). But the most important study was Wollny's (1902) on SOM decomposition. Concerning nitrogen mineralization, Schloesing and Müntz (1877a; 1877b) conducted their famous sewage treatment experiment and, using chloroform as an antiseptic agent, evidenced the major role of bacteria in the nitrification process.

Humus and exchange and sorption properties of soil

The notion of colloid applied to humus (Berzelius, 1839; van Bemmelen, 1888) gave birth to studies on exchange and surface properties of SOM by Gedroiz (1925, in Waksman, 1938), Tiulin (1926; 1927; 1938 in Waksman, 1938; see also Chernianskii, 2000), Mitchell (1932), Turner (1932 in Waksman, 1938) and the emergence of the concept of "organo-clayey complex" or "complexe argilo-humique" of 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), followed by Fickendey (1906, in Waksman, 1938), Oden (1919, in Waksman, 1938), Gedroiz (1925, in Waksman, 1938), and Tiulin (1927 in Waksman, 1938) on the nature of organic films at the surface of mineral particles.

Humus and aggregation

Schloesing (1874) was among the first to study the effect of humates on flocculation processes.

In 1913, Dumont published his unusual work "Agrochimie", a book seldom quoted in the literature that is entirely based on the concept of soil aggregates ("agrégats terreux"). It provides a detailed description of the formation, composition and properties of these aggregates. Dumont distinguishes skeletal or inert material, and cements. The organo-mineral composition of both the skeleton and cements is studied on chemical and physical fractionations. Two kinds of humus are distinguished and functionally opposed, depending on their source ("original" - plant-derived - and "microbial"). The microbial humus is the "active humus" that is more involved in agrochemical cycles and especially nitrification.

Studies on humus, aggregation and soil conservation increased significantly later in the 1930's with the works of Tiulin (1933), Sokolovski (1933), Baver (1934), Anne (1935) and Myers (1937).

Other aspects

In his brilliant "Humus. Origin, chemical composition and importance in nature", Waksman (1938) lists, in addition to the role of humus in agriculture, several other functions of humus, such as solar energy storage, formation or decomposition of substances injurious or favorable to soil biota (plant, fauna and micro-organisms) and the curative effect of organic complexes from humus origin or soil organisms on human beings.

In his conclusion "Humus as an organic system", Waksman writes that humus "probably represents the most important source of Human wealth on this planet", thereby announcing an era of rehabilitation of the agro-ecological role of humus at both local and global scales.

Humus at the heart of early trends in organic farming (1940's)

1.8 Reaction against the ecological misbalance of industrialized agriculture

Beyond the conceptual debate about the substitutability of organic amendments by chemical fertilizers, societal criticisms concerning the sustainability of intensive farming arose as early as the 1930's (Merrill, 1983). The potential of chemical fertilization for increasing crop yield was widely recognized at the end of the 19th century, but by 1940 mineral fertilizers were only one aspect of the second agricultural revolution, and did not account for more than 15% of nutrients exported by crops in 1900 (Boulaine, 1989; Mazoyer and Roudard, 1997). During the first half of the 20th century, intensification derived mainly from laborsaving inventions (e.g. motorization). 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. At the same time more and more evidence was pointing to a link between the decline in soil fertility, the quality of the human diet and human health (Merrill, 1983).

1.9 Humus in the philosophy of organic farming

Bio-functional disorganization and weakening of cropped soils managed without organic practices was recognized early on, but not referred to as such, for soil ecology was still in its infancy. Steiner's lectures (1924) provided the basis for biodynamic agriculture. These lectures referred to holistic and cosmogonic concepts (interrelations between stars, soil and geochemical elements, plant, animals and man) as the basis for a new kind of agriculture that excluded the use of any chemical input. The most influential publications on modern organic farming are from Pfeiffer (1938), Howard (1940; 1952), Balfour (1944) and Rodale (1945) (Scofield, 1986). The main objective they had in common was to improve soil, plant, animal and human health by the biological management of soil fertility. Two fundamental aspects of organic farming system put humus at the heart of cropping sustainability.

The holistic paradigm

In "The Living Soil", Balfour (1944) presents the quintessence of the philosophy of organic farming. The leading hypothesis is that the reason for the obvious – according to Balfour's own criteria – decline in the health of the human race is the decrease in plant health, itself a consequence of the decline in the health of the soil. The philosophy of organic farming is fundamentally holistic and perceives "all life, all creation as being inextricably interrelated, such that something done or not done to one member, part or facet will have an effect on everything else" (Merrill, 1983). This is best illustrated by the biotic pyramid of Albrecht (1975 cited in Merrill, 1983). This pyramid is made of several layers, with the soil as the basement and 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. This hypothesis is well supported by history and archaeology (Hyams, 1976 cited in Merrill, 1983; Olson, 1981).

The Law of Return

Another principle of organic farming is the Law of Return. It stems from the "Living substances cycle" concept, which originated in antiquity and reappeared in treatises on agriculture in the 16^{th} and 17^{th} centuries. This principle seriously influenced Thaër's "Humus theory", to which advocates of organic farming invariably refer. According to this principle, life can be maintained only provided that living beings or at least the residues of their activity and body decomposition are cycled at each step of the biotic pyramid. A crucial process is thus the establishment of organic flows to the soil to maintain its fertility. Since this return is humus-mediated, Balfour (1944), and above all Rusch adopted a skeptical position towards Liebig's "rather naïve theory", and developed a partly rigorous (Balfour and Howard), partly ideological (Rusch) analysis of the agro-ecological role of humus. 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 very rigorous and famous technical handbooks for the production of compost, which he termed "manufactured humus".

Bridging the gap between concepts and practices: humus as a versatile agro-environmental tool (since the 1940's)

Since the 1940's, humus has been regaining interest due to scientific advances partly inspired by those concerned with organic farming, and to a societal demand for sustainable agro ecosystems capable of providing environmental amenities.

1.10 Constructing an integrated perception of soil

While the holistic temptation to identify soil as a living being affected many of the early advocates of organic farming, ecology has been making major conceptual contributions to the scientific study of humus for the past 60 years. Darwin (1837; 1881; see Feller et al., 2000), and Waksman in his "Humus as an organic system" (in Waksman, 1938), may be considered as the forerunners of soil ecologists. Nevertheless, the extension of the ecosystem concept from the landscape scale to the local soil scale certainly played a determining role in the birth of soil ecology, the last frontier in agricultural sciences (Tansley, 1935; Andre et al., 1994).

Within soil ecology, humus has regained a central position as an interface for mineral, faunal and plant components. Today, it is recognized that humus influences plant growth both directly as a balanced and progressive source of nutrients, and also indirectly as a source of nutrients and energy for heterotrophic soil biota, which tightly controls plant nutrition (Myers et al., 1994; Neher, 1999).

For the last two decades, general conceptual advances have also stressed the aptitude of ecosystems - based on their internal organization - to escape constraints of the abiotic environment by building biotic buffers or even modifying abiotic factors (Perry et al., 1989). In terrestrial ecology, humus 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 humus 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_(Straskraba et al., 1999). They suggest that soil structure and organization can be largely controlled by soil biota at the cost of energy – mostly carbon-mediated – dissipation, thus implying SOM recycling (Perry et al., 1989). Therefore, a potential breakthrough in the study of humus 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 humus (e.g. modeling of the soil food web, quantification of soil gaseous carbon emissions). This fits well with Balfour's definition of fertility: "the capacity of soil to receive, store and transmit energy" (Balfour, 1976 in Merrill, 1983).

Fieldwork – especially that in tropical agro-ecology – has also recently called for a reassessment of the real role of humus in plant production (Woomer et al., 1994). On the one hand, mineral fertilization of tropical soils without organic inputs has indeed proved to be ecologically non-sustainable (Mokwunye and Hammond, 1992). On the other hand, biological control of fertility with regard to other abiotic factors is tighter at low latitudes, although temperate and tropical soils do not differ much in the quality of their humus but rather in the rate of decomposition of SOM (Jenkinson and Ayanaba, 1977; Greenland et al., 1992).

1.11 Meeting a growing societal demand for sustainable farming practices

The renewed interest in the study of humus 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) right at the beginning of the oil crisis. He - and later other authors such as Hall and Hall (1993) and Izac (1997) - put forward objective criticisms concerning the true costs of substitution maintenance in modern agriculture. 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 in agro-ecosystems (Izac and Swift, 1994) and to the reinsertion of organic cycling and humus management in agricultural practices (Gardner, 1998).

1.12 Towards a societal support of eco-agriculture

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 scientists, farmers with their practical experience, and finally government with its agricultural policy has been progressively reduced since the 1950's, primarily in the field of organic farming, thereby improving the place of humus management in the definition of new cropping schemes. In Europe for instance, research stations in organic farming founded as early as 1939 (Haughley Research Trust in UK, by Balfour), 1950 (Germany) or the mid seventies (Switzerland, Netherlands) were originally privately funded, but are now partly financed by the state (Krell, 1997). At a more global level, the International Federation of Organic Agriculture Movements, created in 1972, held its first international conference in 1977, and by 1996 about 400 papers were already being presented. Increased adoption world wide of agroforestry, and of composting, mulching and direct sowing 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.

Humus and global change

Within the scope of global change related to man-induced release of greenhouse gases in the atmosphere, global carbon transfers from and to the soil have been receiving increasing attention for more than a decade now (Schlesinger et al., 2000). The carbon pool in the world's soils is three times that in the atmosphere (IPCC, 2000). Any change in the belowground pools resulting from changes in land-use (conversion to crop or pasture, afforestation), will thus have a great impact on carbon concentration in the atmosphere. Most carbon flows are mediated by humus, hence the numerous studies on the soil carbon 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 carbon sequestration capacity, but figures published for belowground carbon sequestration are usually not very accurate, and this underlines, among other things, that knowledge about humus storage determinants is still very limited.

Conclusion

Before 1840, the role of humus in plant nutrition was controversial; theories published by advocates of humus, which claimed material assimilation of humus by plant roots, were unfortunately based on unverified facts and sometimes even on myths. But at that time, agricultural practices tallied with scientific theory. During the mineralist period, humus management was excluded from official theories on soil fertility and consequently from intensified cropping schemes.

From 1940 onward, clear evidence of the decline in soil quality in the field, scientific advances in agro-ecology at least partly triggered by holistic philosophies concerning organic farming, and awareness of the environmental amenities provided by soil organic matter have led to the promotion of humus as a more or less renewable resource. Over the past three centuries the passion for humus can be described by a sine curve, both from the viewpoint of scientific concepts and that of field practices. Agro-economic and environmental problems resulting from the mineralist dogma and the latest integrative advances in soil science partly inspired by a holistic approach to the functioning of ecosystems now support a humus-centered vision of sustainable farming. During the few past decades Thaër's "humus theory" has been partially rehabilitated. Thaër was right when he asserted that plant growth relied on the consumption of humus. His mistake was to believe that humus was consumed directly by the plant (heterophic hypothesis), while progress in soil ecology suggests that humus is in fact a key factor in soil fertility due to its crucial position in biogeochemical cycles and thus in the control of microbial and faunal metabolisms.

The history of the humus concept related to concepts of fertility and sustainability is one example among others of how fruitful it is for science to shift from a reductionist approach to a holistic one. Furthermore, the rehabilitation of the humus concept has greatly benefited from a continuous amplification of the scale at which it was considered, first a local, soil-fertility related scale, later regional, and finally global.

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