HUMUS FORMATION AND C-FIXATION DEPENDING ON SOIL MANAGEMENT

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INTRODUCTION

Soil plays a leading role in the sustainability of both natural and human-managed ecosystems. It constitutes a temporal reservoir in the water cycle, to which it filters in the first metres of its journey towards the aquifers, and acts as support to the vegetation, to which supplies water and nutrients. Ecosystems can be maintained indefinitely provided the climate keeps within some limits and does not suffer any outside aggressions such as those caused by acid rain, etc.

The dynamics of the organic matter in the soil is a key in the soil/vegetation system: the vegetation extracts the nutrients it needs from the soil and incorporates them into its biomass; each year, an important amount of organic matter enters the soil through dead plant residues, where, due to micro-organisms action, it turns into humus, which, in turn, is mineralized throughout the year in a low proportion (1-3%); in the mineralization process of the humus, the nutrients in the latter are released and made available to plants for their nutrition, then they are incorporated into live plant matter, thus closing the cycle. In balanced systems, like, usually, natural ecosystems, the amount of humus generated each year from the fresh organic matter incorporated into the soil is the same as that mineralized, so that the soil humus levels are maintained.

Humus is not only of importance for its regeneration role but, also, together with clay, it makes up the colloidal fraction of the soil, responsible on one hand for its chemical fertility, and, on the other, for the development of its structure or aggregates, which increase soil resistance to erosion with respect to soil with disaggregated particles. Thanks to its structure, it develops a secondary porosity (or interaggregates), with a larger diameter than the primary, textural porosity or intra-aggregates; many fine-textured soils permit water and air circulation as they are favoured by the soil structure's development. In another direction, humus has a great capacity to retain exchange cations, and to adsorb and complex metals, heavy elements and other ions noxious to the biotype, so that it to a great extent reinforces its role of being a soil filter for the water flowing through it.

When men became farmers, they cut down and cleared away the natural vegetation to cultivate the land, so that the equilibrium between the humus formation and destruction rates was upset as an important amount of biomass was removed from the system. During the ancient civilizations and up to the beginning of the 20th century, tillage implements were animal-drawn and an important part of the organic matter extracted with the harvests returned with the manure produced from those animals and the organic residues generated by humans. With the industrialization and mechanization of the countryside, the panorama changed; the organic matter returns diminished and the soil humus mineralization was accelerated due to the number of agricultural tasks becoming easier and increasing, which incremented the organic matter mineralization rate as the soil/air surface did so (Raikosky XXX).

Thus, the level of the organic carbon content in the soil is conditioned by the difference between the inputs of new organic remains, and the outputs via exportation, mineralization and erosion. In cultivated soils, the main organic C input comes from harvest residues, whose content in C is around the order of 50% of the dry weight of the residues (Crovetto, 2002). It is estimated that most of the carbon supplied with the remains is lost in the atmosphere in the form of $CO_{2,}$ and that only 20-30% of the C contributes to increasing the organic carbon in the soil (Voroney *et al.*, 1989). However, this contribution in soils cultivated in the traditional manner, in which tillage is often abusively used, is not sufficient to maintain the humus content, so important for keeping up the natural fertility of the soil, on a short/medium term.

The evolution of organic matter in the soil is due to micro-organism activities; as we said before4, these, in a mixed process of mineralization and humification, turn it more or less rapidly into humus, considerably reducing the C:N ratio in the process; in turn, the humus, also under the action of the microorganisms, is destroyed in a small annual proportion, in a mineralization process, in which the nutrients in the contents are released and make themselves available to plants. The balance between both processes is the sign of an balanced microbial activity and of good environment and edaphic conditions, which are the main guarantee of the sustainability of the system and of its fertility.

TRADITIONAL AGRICULTURE SYSTEMS (TA), VERSUS CONSERVATIVE AGRICULTURE SYSTEMS (CA)

One of the consequences of traditional tillage is the diminution of the content of organic carbon in the soil. This is the result of:

- The lesser input of organic matter in the form of harvest residues,
- The higher humus mineralization rate caused by tillage, and
- The higher erosion rate which originates major losses of organic matter along with the mineral.

In conventional or traditional agriculture systems, the soil preparation tasks for sowing leaves the soil surface bare for long periods of time, and, thus, it is exposed to the action of rain and other erosion agents. The consequences of this are that the organic matter in most agricultural soils is decreasing as a result of the intensive agriculture practised (EEA, 1998). Figure 1 shows some examples, which demonstrate the speed at which the humus mineralization process acts under tillage.

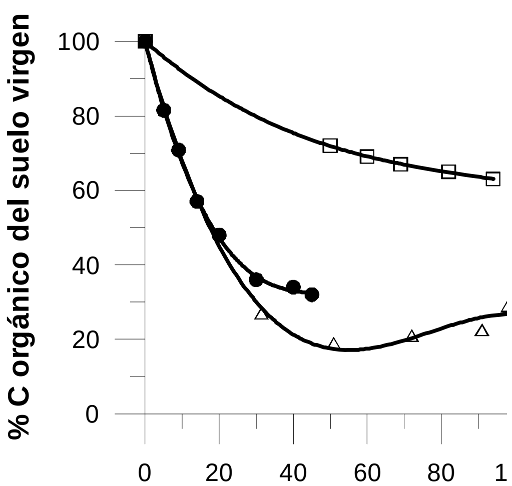

Figure1.- Decrease in organic C content in several cultivated soils. In ordinates percentage respect virgin soil; in abscises years under tillage. Circles Queensland, Australia (Dalal & Myer, 1986). Triangles, Missouri,USA (Balesdent *et al.*, 1988). Squares, Oregon, USA (Rasmussen *et al.*, 1989)

According Kinsella, (1995), and Heenan *et al.* (2004), after about 15 to 20 years of intensive tillage, the organic carbon content in most agricultural soils in semi-arid areas is reduced by half. But the reduction in soil organic matter content due to tillage is particularly important in soils under tropical and subtropical conditions where soil carbon is oxidised quickly.

As a result, the reduction in the inherent productive capacity of intensively farmed soils is generally masked by heavier applications of fertilizers, at an ever increasing cost. But this is only a temporary solution, and, over time, the continued reduction in organic matter levels leads to reduced availability of plant nutrients and increased susceptibility to water stress, resulting in yield reduction that cannot be stopped just by applying more fertiliser inputs. In short, farming as now widely practised, is not sustainable in the long run, from either environmental or economic viewpoints.

Sanchez *et al.* (2003), in their formula for evaluating soil productivity, introduced a new parameter, m, referring to saturation by organic matter and which is related to the percentage of organic matter content in the soil in relation to that of the same type of virgin soil under a natural vegetation cover. This parameter could serve as a work tool for calculating the amount of CO_2 emitted by the soil into the atmosphere as a consequence of the change in soil use from natural to agricultural. It becomes clear that in the examples in Figure 2, in the cultivated soils referred to, this threshold of 80% of carbon content in the corresponding soils under natural vegetation was exceeded. Following this trend, in the acid raña soils of Cañamero (Cáceres), the initiation of the cultivation of virgin soils with cork oaks (Plinthic Palehumults, Soil Survey Staff, 1999) caused drastic declines in organic carbon content in the top 50 cm of the soils, so that in 40 – 50 years of tillage the carbon content dropped from 6% in virgin soil to, in extreme cases, less than 3%, with the soil evolving towards becoming a plinthic Palexerult; in this process, an emission of over 300 megagrammes of CO_2/ha (Mariscal *et al.*, 2006) was recorded.

The organic matter in the soil is made up of a complex set of components, which behave differently in the mineralization process. For that reason, a distinction is often made between its labile or active fraction, more easily mineralizable (Blair *et al.*, 1995; Weil *et al.*, 2003; McLauchlan and Hobbie, 2004) as opposed to the recalcitrant or passive bulk of SOM, which is very slowly mineralized by the action of soil micro-organisms (Wander, 2004).

The lability of organic matter in soil depends on its chemical composition (substances of a high molecular weight and aromatic compounds increase the recalcitrant character and proportion of carbon in OM), and on aggregates stability what provide effective physical protection (Cambardella and Elliot, 1992; McLauchlan and Hobbie, 2004; Pulleman *et al.*, 2005). The labile fractions of soil organic matter include particulate organic matter (POM) (Cambardella and Elliot, 1992) and dissolved organic matter (Saviozzi *et al.*, 2001), among others. POM consists of plant fragments at variable stages of decomposition that are readily attacked by enzymes in soil micro-organisms (Cambardella and Elliot, 1992); it is usually present as aggregates larger than 53 μm in size, whether bound to smaller aggregates (free or inter-aggregate particulate organic matter, PMO_f) or within micro--aggregates (occluded or within-aggregate particulate organic matter, PMO_o) (Besnard *et al.*, 1996; Six *et al.*, 2001; Kölbl *et al.*, 2005). This fraction is directly related to structure development and readily mineralized when a virgin soil is tilled (Cambardella and Elliot, 1993; Bossuyt *et al.*, 2002) –particularly the inter-aggregate fraction which plays an important paper in the natural ecosystem 's fertility sustainability (Salas *et al.*, 2003). POM is severely affected by tillage (Franzluebbers, A.J., Arshad 1996; 1997); in soils under oak trees at Cañamero's raña surface, POM reaches the 60% of total organic matter (TOM) in the uppermost 5 cm, and 24% (TOM) in the 5 – 25 cm soil layer whereas at the same surface, in soils under olive trees POM only reaches 15% , and 8,2 % at same depths (Mariscal, 2008). In this raña surface, Palexerults degraded by tillage after 5 years of permanent pasture increased the POM in the 5 cm uppermost soil layer from A to B (Mariscal 2008)

Conservation agriculture (CA) originated in the U.S.A. in the 1950's, as an alternative to traditional agriculture (TA), and it became a means of halting erosion in agricultural soils and regenerating the properties related to its quality which had been deteriorated by tillage carried out continuously for long periods of time. The "quality" concept is very much linked to that of sustainability; quality is not defined as a function of a specific use but it is more related to its multi-functionality, and, according to Karlen *et al.*(1997), it can be described as "the capacity of the soil to function within the limits of a natural or managed ecosystem, to sustain plant and animal productivity, to maintain or improve air and water quality, and to preserve human health and the habitat". There is, thus, a broad dependence between soil quality and that of the environment to which it belongs.

There are various conservation agriculture forms:

a) Direct drilling: No tillage is done between harvesting and the establishment of the next crop, which is sown directly, conserving the stubble and the residues of the previous crop. This is the modality which provides the greatest protection to the soil against the erosive action of rain. Weeds are controlled by herbicides with a low impact on the environment.
b) Minimal tillage: This permits vertical tillage with chisel ploughs, cultivators, etc., which do not overturn the top layer of the soil. The amount of remains from the previous crop depends on the number of tillage actions done and on their aggressivity.
c) Plant covers. Adapted to woody crops: Strips of herbaceous vegetation, specifically sown or spontaneous, are established between the rows of trees, and they are controlled by mechanical reaping, chemical elimination, or with the help of a low-intensity cattle action when the dry season begins to prevent competition for water with the crops; the stubble is left on the surface. This form of CA is highly effective for erosion defence in vineyard and olive grove soils, which are frequently planted in areas with steep slopes (Francia *et al.* 2000).

The pillars holding up CA and which mark the main differences with regard to conventional agriculture are:

1) A minimal or zero mechanical alteration of the soil
2) Direct drilling onto the remains of previous crops
3) Permanent cover on soil surface with residues from previous and present harvests
4) The compulsory establishment of crop rotations and green fertilization

Conservation Agriculture generates a larger input of organic matter in the soil, which, as opposed to the higher rate of CO_2 emission caused by tillage in TA, makes this management régime reinforce its role as a CO_2 sink (Reikosky, 2001). In the U.S. maize belt, the transformation of TA to CA would mean an atmospheric C-fixation of the order of 3.6 Mt/year in the next 100 years (360 Mt/100 years). Gebhart *et al.*, (1994) estimated that in the 17 million hectares included in the U.S.A. Conservation Programme, which encompass lands with a high erosion risk converted into permanent no-till fields, a 45% reduction in the CO_2 emitted in that country's agricultural areas would be contributed.

Lacasta *et al.* (2005), on an estate located in the province of Toledo, found that direct drilling, after 21 years, had increased the organic carbon content in the first 25 cm of surface soil of an Inceptisol by 15% compared to the initial value (0.66%, whereas the use of a mouldboard plough impoverished that content by 15% and that of a chisel plough by 3%. López Fando *et al.* (2005), after 11 years of managing a calcic Luvisol under direct drilling, found increases of 4 t ha^{-1} in carbon content with respect to tilled soils.In the Guadalquivir valley, Ordoñez *et al.* (2007), after 21 years of cultivation by direct drilling in a clayey soil (chromic Haploxeret, Soil Survey Staff, 1999), found that the organic matter content in the first 50 cm had increased by 1%, which signified an increment of 40% of the initial content and a C-fixation of 18 t/ha , equivalent to 66.6 t/ha of CO_2 (Figure 1). This rate, of the order of 1 t/ha yearly, is the same as that found by Arrue (1997).

A minimal period of time is required by CA to trigger any significant increases in OM content, which mainly depends on the climate and the crops (Hernanz *et al.*, 2002). Sombrero *et al.* (2006), in trials carried out in the province of Burgos did not find any significant differences inorganic matter contents from non tillage in the first 15 cm of the soil until 5 years had gone by. With the time, the differences increased, and, thus, at 8 and 10 years, the OM increases were of the order of 18 and 20%, respectively.

One aspect which should be emphasized is that the burial of plant residues by tillage tasks carried out in traditional agriculture, causes a different soil organic matter dynamics to that produced in natural ecosystems, into which it is incorporated and evolves on and from the soil surface. Conversely, conservation agriculture, by leaving harvest remains on the surface, induces an OM dynamics analogous to that occurring in natural ecosystems. The result is that with CA there is an increase in the stratification of organic matter in its vertical distribution, which is taken to be a sign of the recovery of the quality of agricultural soils degraded by tillage (Franzluebbers, 2002; Moreno *et al.*, 2005). An important part of this humified organic matter on the surface is transported towards the inside of the soil by worms, whose population is very much reinforced by CA (Cantero *et al.*, 2004; Bescansa *et al.*, 2005). Table 1 shows percentage data of organic harvest residues which remain on the soil surface and protect it depending on the different agricultural tasks or forms of use applied to it:

Table 1.- Percentage of surface residues after tillage on a stubble given with different implements (Stott, 1991)

Mouldboard plough	2-4%
Disk plough	30-6%
Chisel plough	50-75%
Direct drilling	90-95%

The surface layer of organic remains generated with CA plays a mulch role, which is highly beneficial for saving water as it stops evaporation losses; this surface layer also regularizes the temperature of the top 25-30 cm of the soil. As a result, CA encourages more favourable environment conditions to micro-organisms, which, together with the increase in organic matter, generates a much more propitious atmosphere in the soil for biological activity.

In this respect, it should be take into account that, in soil, most of the edaphic processes implicated in its biological activity and nutrient cycle are circumscribed to its top 25-40 cm, where the rhizophere is located, i.e. the area of the soil with the highest root density, and where there is a close relationship between the soil, the plants and micro- and macro-organisms; any human intervention affecting any of these three systems will have some consequences on the other two. In the rhizosphere, plants constitute the main origin of organic carbon, which is the primary energy source of the organisms in the soil. The latter make an effective contribution to the development of aggregates and to the recycling of the nutrients contained in the organic remains. Within the rhizosphere, a leading role is played by vesicule-arbuscular mycorrhizal fungi (VAMF), which are essential to the establishment, growth and survival of many plants. They are considered as being authentic "pipe-lines" for the transport from the soil to the plant of water and nutrients in exchange for providing a direct access to the fungus of photosynthesis products rich in carbon. They also permit the entry to plants of sometimes rarely accessible nutrients like P, Ca, Zn and Cu (Clapperton et al., 1997), and increase the resistance of host plants to root diseases (Clapperton & Ryan, 2001). In fact, the colonization degree of HMVA in soils, and therefore, the advantages due to them, are seen to be greatly reduced by tillage, as well as by the presence in rotations of plant crops not compatible with the HMVA.

Consequently, and always based on scientific results, there is currently a notable trend in favour of the adoption of conservation techniques in order to prevent soil carbon losses and the extra emissions of CO_2 into the atmosphere, but also, at the same time, to increase the carbon content in the soil (Lal, 2004; Pautian *et al.*, 1998; Reicosky, 2005). The "key" to a sustainable future is to move towards more ecologically friendly farming systems that are more effective in harnessing nature to sustain higher levels of productivity.

Conservative Agriculture and other similar systems for intensive farming that lead to the progressive build-up of soil organic matter have been successfully tested and applied by farmers in many parts of the world over the past 40 years. Though these systems vary in the technologies applied across countries, climates, soils and crop types, their common features are that they enable farmers to create conditions more favourable to biotic activity in the soil through:

(a) maintaining, a year-round cover over the soil provided by the current crop, including specially introduced cover crops and intercrops and/or the mulch provided by retained residues from the previous crop;
(b) minimising soil disturbance by tillage, eliminating tillage altogether once the soil has been brought to good condition, and
(c) diversifying crop rotations, sequences and combinations, adapted to local socio-economic and environmental conditions, which contribute to maintaining biodiversity above and in the soil, and help avoid build-up of pest populations within the spectrum of soil inhabitants.

Because of the benefits that CA systems generate in terms of yield, sustainability of land use, etc., the area under Conservative Agriculture systems has been growing exponentially. It is estimated that, worldwide, there are now almost 100 million hectares of arable crops which are grown each year without tillage. But in general, except in a few countries, however, these approaches to sustainable farming have not been introduced, and the total area under CA is still very small relative to areas farmed using tillage.

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