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Soil organic matter in the sustainable agriculture: Source or sink of carbon?

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Abstract

Stocks of Soil Organic Matter (SOM) are controlled by the balance between carbon inputs derived from plant production and outputs through decomposition processes mediated by heterotrophs. The importance and function of SOM is largely due to its dynamic nature, being continuously synthesised, mineralised and rearranged. Besides CO₂ production, SOM decomposition provides metabolic energy for microorganisms and mineral nutrients available for plant uptake. Intensive agriculture stimulates the rate of decomposition, because the physical disturbance exposes

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the previously protected organic matter to biological activity, increasing oxygen diffusion and enhancing C mineralisation. Moreover, a large amount of crop products are removed, thus subtracting C to the ecosystems. Raising the soil C content means increasing the C input, decreasing the output or a combination of the two through improved land management. In particular, in agricultural soils, increasing C inputs is the major pathway for increasing soil C storage, without depleting nutrients released through SOM mineralization. This could be achieved by the use of animal manure, crop residues, sewage sludge and compost, improving rotations with higher C inputs to the soil and reducing soil disturbance with zero tillage practices.

1. Introduction

There is a large literature on the physico-chemical nature of Soil Organic Matter (SOM) and related factors. For many centuries most farming practices were based on the empirical observations that additions of relatively fresh organic materials improved both soil fertility and crop yields. This perception is still persisting and manure, compost, crop residues, sewage sludge and others are believed to be a good system to maintain soil quality and sustainability, often forgetting the importance of the presence and role of the “inert” fraction of SOM. The differentiation of SOM into “active” and “inert” or “old” fractions is important in terms of SOM turnover [1]. The easily oxidisable fraction is considered to have an half-life less than one year, while the inert fractions have half-lives up to 25 years or more. The ratio between the short-term and long-term SOM is generally assumed to be constant, with a fraction of inert SOM replacing the mineralised fraction of active SOM, and recalcitrant molecules of organic residues contributing to the formation of inert SOM fractions. However, it is important to realize that the formation of such equilibrium relies on a fragile balance and can be subjected to short-term disturbance by agriculture, which changes both quality and quantity of residues input and affects the soil ecosystem thus influencing the microbial activity and organic matter dynamics.

Stocks of SOM are controlled by the balance between carbon inputs derived from plant production and outputs arising from decomposition processes mediated by heterotrophs. The unbalance between inputs and output to SOM is reflected by the alterations of carbon and nitrogen elemental cycles [2]. At the global scale, climate plays a significant role in the dynamics and storage of SOM; however, at the regional scale, factors such as soil texture and vegetation type may be stronger determinants of variability of SOM content, as well as its rates of accumulation and decomposition.

2. Soil organic matter and its ecological functions

SOM is considered to have some important functions on soil both on-site and off-site. It reduces susceptibility to erosion thus reducing sediment load in streams and rivers; it is energy substrate for soil biota, leading to increase soil biodiversity and supporting biodegradation of contaminants; it buffers against sudden fluctuations in soil reaction (pH) filtering agricultural chemicals and allowing their degradation by soil microbes. However, it has to be considered the elevated heterogeneity of SOM and its fractions exerting different roles in the ecosystem balance. SOM is known to be important in the development of soil structure, but generally it is the inert soil organic material to have an important role in the stabilisation of aggregates. Crop nutrition is mainly due to the active and water-soluble fractions while old SOM makes no direct contribution to crop nutrition. Nevertheless, the inert portion can have a direct effect on soil available water or indirect effects changing the pore size distribution, associated to the active fraction. The dissolved organic fraction has a positive effect on root growth and nutrient uptake by plants. All fractions contribute to the chelating and buffering soil properties allowing nutrient exchange, reducing soil management and contributing to the pH dependent Cation Exchange Capacity.

It is known that soil organic matter is storing a great quantity of carbon. It is considered to be 1500 Pg to a depth of 1m, the double of the amount present in the atmosphere and almost three times of C stocked in biotic pool [3]. There has been an evident decline of C in cultivated soils in recent years, because agriculture tends to reduce organic matter. In fact, most of the organic litter are not returning to the soil, tillage practice makes SOM more accessible to biological decay and agriculture intensifies erosion of surface C-rich soil.

In Table 1 the emission of CO₂ is reported comparing two recent decades.

Table 1. CO₂ budget (redrawn from [4, 5]).

		1980-1989 Pg C/Year		1990-1999 Pg C/Year	
Emission	Fossil Fuel	5.4±0.4	7.1	6.3±0.4	8.5
	Land use Change	1.7±0.8		2.2±0.8	
Sinks	Increase Atmospheric Concentration	-3.3±0.2	5.0	-2.9±0.1	5.3
	Absorption by the Oceans	-1.7±0.8		-2.4±0.8	
	Unknown Terrestrial Sink	2.1±1.3		3.2±1.3	

There are some estimates of the historical loss of C from geological (Soil Inorganic Carbon, SIC) and terrestrial pools and transfer of this C into the atmosphere. From 1850 to 1998 emissions from land use change related to deforestation, biomass burning, conversion of natural to agricultural systems and the ploughing of soils are estimated at 136 Pg C [6]. World soils historically have been major source of atmospheric enrichment of CO₂: until the 1950s more C was emitted into the atmosphere from land use change and soil cultivation than from fossil fuel combustion [4] and nowadays it accounts for 20% of the global emissions [7].

The components involved in such emission are principally the decomposition of vegetation, the mineralisation/oxidation of both labile and stable SOM and the production of CO₂ from soil that is enhanced by agricultural activities. Soil temperature, moisture regime and texture strongly influence the emission and, as it is known, the conversion of natural to agricultural ecosystems increases the soil temperature and decreases soil moisture mainly in drained agricultural soils, strongly influencing SOM pool and dynamic. A typical example, reported by Sommer and co-authors [8], is the eastern Amazon of Brazil, Para' state. Deforestation, land use change and conversion to agricultural ecosystem under permanent annual cropping culture over last 100 years determined a decrease of SOM pool by 30 to 50 Mg C/ha. Agricultural practices are strongly enhancing losses of SOM regardless the climate and soil type, increasing mineralisation, allowing a closer contact between soil and crop residues, physically breaking aggregates and exposing protect SOM to microbial activity. In fact, organic matter can be protected against decomposition when it is located in pores that are not accessible to bacteria and fungi, or inside large aggregates which become partially anaerobic because of slow O₂ diffusion. Moreover, soil aggregates are held together by microbial debris and fungal hyphae, roots and polysaccharides so that the decrease amount of any of these agents will reduce the aggregate stability. All this is in danger when tillage is performed.

3. Soil organic matter and carbon balance

Atmospheric CO₂ enters terrestrial biomass *via* photosynthesis, at a rate of 120 Pg C per year (gross primary production). Half of that is soon released as CO₂ by plant respiration, so that the net primary production (NPP) is about 60 Pg/year, stored at least temporarily in plant tissue, but most frequently it reaches soil because of tissues and organs senescence. Under natural conditions, heterotrophic respiration, largely due to microorganisms, and fire return back to the atmosphere an amount of C as CO₂ roughly equivalent to NPP. In agricultural cropping systems, the largest part of C is stored in the soil. Input of C is determined by the NPP and the fraction of it remaining in the field. Loss of C is determined by decomposition and loss of top soils by

erosion. The rate of decomposition is controlled by environmental conditions and soil physical and chemical characteristics.

Excessive exploitation and mismanagement has a strong influence on the decline of soil quality, producing an alteration of physical, chemical and biological parameters and inducing SOM reduction. Soil degradation, besides to decreasing biomass production and reducing the amount of residues returning to the soil, accelerates soil erosion determining a negative effect on SOM pool. Long term agricultural experiments in North America and Europe indicate that SOM and carbon are lost during intensive cultivation, typically showing exponential decline after the early phase of cultivation of natural soils and a constant loss along the subsequent years [9].

The concentration of CO₂ in the atmosphere has raised after the industrial revolution for energy production burning fossil fuels and for the land use changes. The constant increase would be more rapid but a large amount of CO₂ from the atmosphere is removed and stored in oceans and terrestrial ecosystems.

The majority of C stored in global vegetation occurs in forests. The growth of trees and the preservation of old forests is of prime importance in regulating the size of the overall terrestrial sink. In temperate and boreal forests the amount of C stored in the soil is about four times as high as that stored in the vegetation, and 33% higher than total C storage in tropical forests [10]. Thus, there is considerable potential for long-term sequestration of C in the soils of temperate/boreal forests where, in biological stable condition or mineral-bound form, it could have a residence time of hundred or thousand of years. In grassland there is generally more soil organic C than under cropland [11], due to several factors including lack of disturbance, greater return of plant residues and high root biomass. Grazing practices increases grassland productivity due to a more rapid annual turnover of shoot material and also to higher plant biodiversity.

There is a growing interest of the scientific community in evaluating the possibility to reduce soil C emissions, developing options for soil C sequestration. The term soil C sequestration implies net removal of atmospheric CO₂ by plants and its storage as soil organic matter. Processes of SOM sequestration include humification, aggregation, deep incorporation of C in the subsoil and limestone formation [4].

Humification involves conversion of plant and animal residues into complex humic substances, which are stable and recalcitrant. Not only carbon structures are needed for the conversion but also N, S, P and several micronutrients are involved in the process.

Aggregation involves the formation of organo-mineral complexes and stable micro-aggregates that protect C from microbial processes. SOM that becomes encrusted by mineral material dominated by small pores may become

the centre of water-stable aggregates. Microbial by-products of organic residues oxidation bind inorganic particles and increase the strength of the association and enhance aggregate stability. The fungal by-product glomalin has been identified as important in the formation of soil structure and its concentration increases with conversion in a no-till system [12]. And at the end, calcification involves formation of pedogenic or secondary carbonates and leaching of carbonates in the ground water.

4. Carbon balance and agriculture

Agriculture is, in this contest, an anthropogenic manipulation of C and the management of agro-ecosystems is an important strategy to enhance C uptake, decreasing emission.

Soil organic matter is the main C stock of interest in agricultural systems. The biomass C pool on agricultural ecosystems is composed of small size vegetation, generally annual plants, which is removed at least once a year by harvesting. Thus there is little capacity for long term accumulation of standing stocks of crop biomass, as for example in forest vegetation. Humans are using 10-50% of terrestrial photosynthesis products [13], taking possession of C cycle, re-routing it and sometimes even suppressing it entirely.

The sink capacity of soil organic matter for atmospheric CO₂ can be greatly enhanced by the restoration or rehabilitation of degraded soils and ecosystems and by converting agriculturally marginal soils to natural vegetation. These strategies conserve soil and water, improve soil quality and enhance C pool.

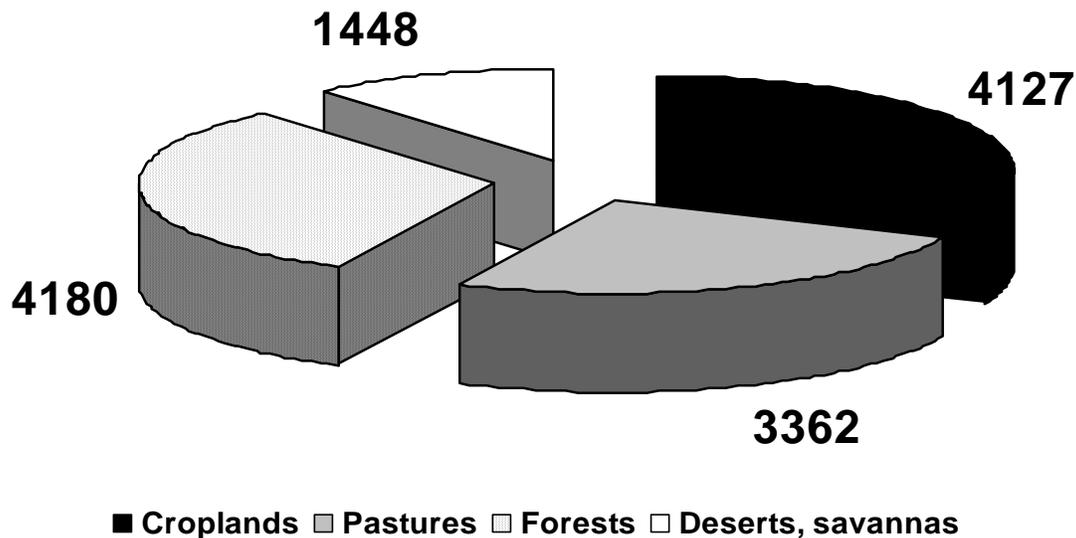


Figure 1. Land Use in the World (millions of ha). Data from [14].

Few studies have estimated agricultural soil carbon sequestration potentials. Available literature has been reviewed by Freibauer and co-authors [15] where technical and economically possible potentials for carbon sequestration in the agricultural soils of Europe by 2008-2012 are analysed. The authors provide a quantitative estimation of C absorption potential per hectare and the surface of agricultural land that is available and suitable for the implementation of those measures. Results indicate that agricultural soils of EU can sequester up, during Kyoto commitment, less than one fifth of the theoretical potential, equivalent to 2% of the European anthropogenic emission. We will come back later on the Freibauer's results.

Globally the land use change with the largest influence on C cycle was the expansion of agriculture [5]. In the last four centuries, the land area devoted to pasture and crops increased from negligible value to about 35% of global area, largely at expense of forests and grasslands (Figure 1). The change has depleted the reserves of stored C. But why?

C stocks in an ecosystem are function of inputs from photosynthesis (net primary production, NPP) and losses from heterotrophic decomposition. The use of land for crop production has an evident effect on stored C that Janzen [5] summarised as follow. Agriculture stimulates the rate of decomposition, because the physical disturbance exposes the previously protected organic matter to biological activity, increasing oxygen diffusion and enhancing C mineralisation. A second effect, sometimes more important, is that a large proportion of crop products are sent away, thus subtracting C, acquired by photosynthesis, to the ecosystems. Only a small part of crop remains in the farm as residues, being many farming systems and the plants used within them, specifically designed to maximize the amount of saleable product. Janzen [5] reports that grassland soils quickly lose a large fraction of their stored C (20-30% in surface layers) soon after initial cultivation. In forest the lost can be even higher where much of the C is in vegetative biomass. Globally, losses of C from land use change have been progressively increasing over the last 150 years. Moreover, an important fraction of C in the atmosphere is due to the fossil fuel burning (Table 1). Despite the existence of important sinks as oceans and terrestrial ecosystems the atmospheric C is increasing every year; the buffer capacity of global systems is not enough.

5. Carbon dynamic in soil

Rapidly rising concentration of atmospheric CO₂ have prompted an abundance of studies on soils as potential C sinks. Literature is recently full of papers on soil C sinks, C sequestration, C sequestering, C storage, C stabilisation, C storing, imagining soil as a trap for C, building up C reserves in the form of humus. In this sense, C in soils is often seen as a very positive position: soil not only removes excess of CO₂ from the air but also improves

soil quality and properties by increasing organic matter, which is known to be the source of energy and nutrients for soil biota.

And here is the first inconsistency: the value of the organic matter is not due to its presence but as fundamental substrate for soil biota. The increase and accumulation of organic matter in a soil depends on the relationship among the plethora of organisms that are living in the soil. They act oxidising the organic residues, producing microbial by-products and transforming the soil in a big incubator. At the end a secondary material is synthesised, the humified soil organic matter, that is slowly mineralised, mainly by microorganisms. In normal conditions the synthesis of SOM and its mineralisation is in equilibrium. This is a central concept in the attempting to define the role of SOM: its importance and function is largely due to its dynamic nature, being continuously synthesised, mineralised and destroyed, as stated many years ago by William Albrecht [16]. A large proportion of the C that enters the soil is returned to the atmosphere through respiration carried out by roots and soil organisms. The distinction between autotrophic (plant) and heterotrophic (microorganisms) respiration in soil is difficult to make and estimates are extremely uncertain. However, the biogenic sources of CO₂ efflux from soil has been distinguished and described by Kuzyakov [17] according to their turnover rates and the mean residence time of C. This partition is important since the autotrophic contribution to soil respiration has no effect on long term C balance in soils, whereas the heterotrophic component will determine whether the soil is a net source or a net sink of CO₂.

In principle, a soil cultivated for row crops would typically lose about 2.5% of its organic C by soil heterotrophic respiration each year [18]. In an agricultural soil, with an intensive management, total loss from the total pool of soil humus is higher than total gains. Generally equilibrium is reached but, if losses continue, degradation of soil quality and productivity would surely result.

Most of CO₂ evolved by heterotrophs is respired by microorganisms such as bacteria, non-micorrhizal and micorrhizal fungi, and actinomycetes. Although the direct contribution of soil macrofauna to CO₂ emission is small, they can greatly increase microbial respiration not only by crumbling plant residues, but also by predation of some groups of microorganisms [17]. However, soil respiration is strongly influenced by a multitude of interacting factors and in most ecosystems it is highly temporally and spatially variable. Humus is a stable pool of C in soil, comprising mostly resistant material, whereas labile C pools, typically including recent leaf, needle and root litter and microbial biomass, are important sources for heterotrophic respiration. In addition, dissolved organic matter (DOM) represents a small and very labile C pool and contains low molecular weight molecules that are quickly assimilated by soil microbial biomass (Table 2).

Table 2. C pools of SOM and their turnover time (adapted from [19, 20]).

Composition	Proportion of total SOM (%)	Turnover time (yr)	Operative Pool
Microbial biomass	0.2-1.4	0.1 - 2	ACTIVE
Dissolved OM	2 - 5	0.1 - 3	
Litter	-	1-3	
Particulate OM	18 - 40	5 – 20	SLOW
Inter - microaggregate	20 - 35	5 - 50	
Humic and fulvic acids	30 - 45	50 - 5000	PASSIVE
Intra - microaggregate	20 - 40	50 - 3000	

The presence of an intensive biological activity working on soil organic matter is the vital aspect of soil fertility. The farmers, in the old time, knew that organic matter must suffer decay and decomposition before serving for appropriate use in the soil. Humus as such can not be used by plants but has to be oxidised into simpler compounds to contribute to the plant mineral nutrition. It is evident that humus value is in its dynamic nature, constantly formed from plant and animal residues and continuously degraded by microorganisms. The measurement of decay is generally utilised by soil researcher to assess soil health and quality, acknowledging the importance of such measurements to evaluate soil performance. In fact, soil respiration is extensively used as indicator of soil quality or health and it is the base for other important indicators which use CO₂ as part of elaborated quotients.

6. Agricultural soils: From C source to C sink

It is evident that all soil C pools have a real dynamic condition and they have been considered for decades the “fuel” for biological machinery of living organisms in soil. Most of the C pools have a beneficial effect on microbial world because are easy and accessible substrates. The result is the production of metabolic energy, nutrients and CO₂. Also plants have benefits; the humus as such is not utilised by vegetation, but its mineralisation produces simpler compounds that are efficiently uptaken by roots. Indeed, lowering soil respiration determines a reduction in the amount of mineral nutrients available for plants uptake, thus inducing a real decrease of primary productivity that in its turn will affect negatively the organic matter inputs to soil. Moreover, the dynamics of soil organic matter has a positive effect also on soil physical (e.g., water retention) and chemical (e.g., ion exchange) properties. It is evident that the value of organic matter in soil is due more to its turnover (decay and synthesis) than to its presence.

Janzen [3] is calling this as “*an apparent paradox*” because “*to build organic C, we may need to stifle respiration*”. In promoting soil as C sink we

arrive to a contradiction, called again by Janzen, a *dilemma*. “if we want microbial activity we have to sacrifice soil organic C; if we want to store more C in soil we must squash microbial activity. So for any patch of land and span of time, we have to choose one – higher soil C or higher respiration”.

But the problem remains: the need to sequester C to overcome global climate change and to improve soil quality developing more sustainable and land management practices. The global estimates of C loss from cultivated soils provide a reference level for the C sequestration that might be achieved through improved soil management (Figure 2). Ecosystem productivity and soil organic matter mineralisation are strongly dependent on environmental conditions. Climate, soil type and past land management have a direct effect on the carbon sequestering potential. The amount of organic C which can be stored in soil is determined by the balance of the input of C from plant and animal residues and the mineralisation of soil organic matter. Any practice that increases net primary productivity or reduces the rate of heterotrophic respiration will increase C storage.

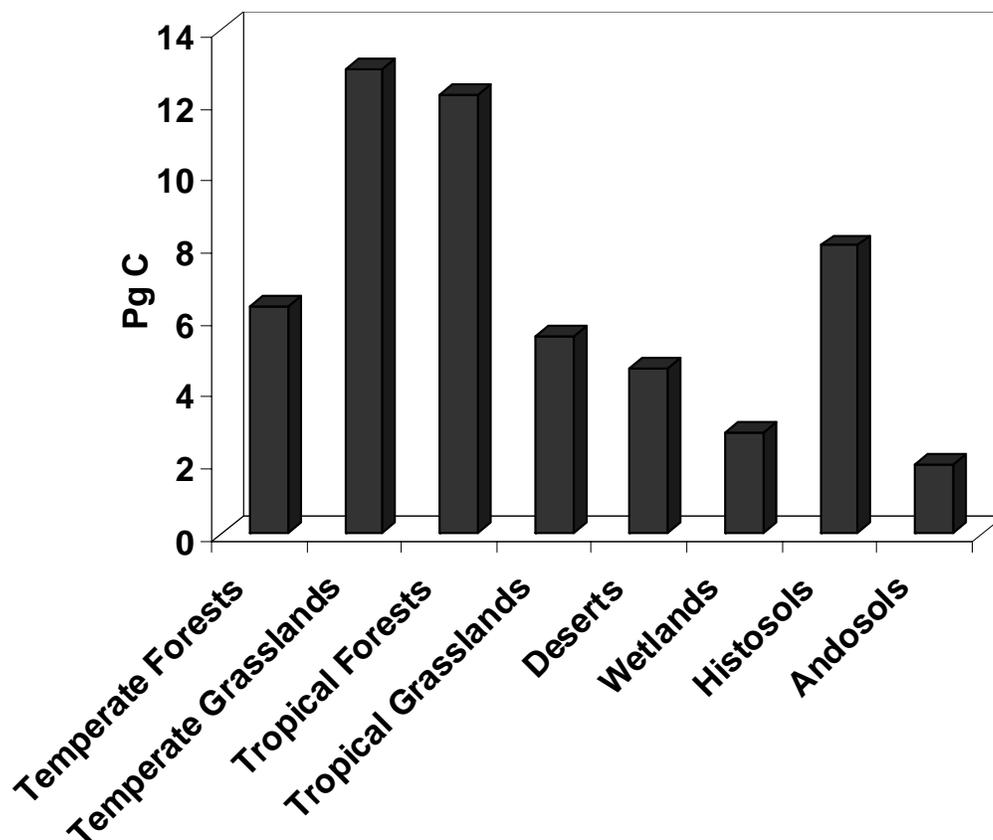


Figure 2. Total estimated historical C loss due to cultivation. Using the distribution of cultivated soils across major groups, their associated C contents, and estimating average losses due to cultivation, yields a current global stock in cultivated lands of 168 Pg C and a historical loss from these soils of 54 Pg C. Data from [21].

In agricultural cropping systems the largest part of the C is stored in the soil. Input of C to soil is determined by the net primary production and the fraction of residues remaining on the field, while loss of C is determined by decomposition and loss of topsoil by erosion. In general, low crop yields, high soil carbon content, and high soil organic matter decomposition rates enhance the loss of C from agricultural soils. Evaluation of current and new management practices for C sequestration should focus on the input and output of soil organic C. Increasing the soil C content means increasing the C input, decreasing the output or a combination of the two through improved management.

Therefore, the *dilemma* can be overtaken by increasing the amount of C entering the soil and in agricultural soils, being depleted in C relative to their native condition, increasing C inputs is the major pathway for increasing soil C storage.

This could be achieved by the use of animal manure, crop residues, sewage sludge and compost, on cropland, and improving rotations with higher C inputs to the soil. Soil can become a C sink also through a reduction in soil disturbance as zero tillage, set-aside land, and the growth of perennial crops, because more C is lost from tilled soils than from soils that are less disturbed [4]. Switching from conventional arable, traditional agriculture to other land uses with higher C inputs or reduced disturbance will favour soil C sequestration. The conversion from intensive mechanical tillage to conservation tillage can favour C storage and the presence of crop residues mulch on soil surface is an integral part of conservation tillage. The adoption of conservation tillage increases soil organic C concentration by reducing soil disturbance, decreasing soil erosion, increasing infiltration and conservation of water and increasing soil biodiversity [4]. Cover crops in rotation cycle can help to enhance C sequestration, but the success of cover crops in improving soil organic C depends on the quality of residues left by the crop and on water availability. In fact, the use of cover crops as short-term green manure does not always enhance soil organic C pool. Moreover, the use of organic manures and compost enhances C pool more than the addition of a similar amount of nutrients as inorganic fertilisers. A huge body of literature is reporting the positive effects that the application of manure and compost have on soil quality and on C pool concentration. Another aspect important in C sequestration policy is the restoration of degraded soils utilising judicious land use. Generally speaking, afforestation through appropriate woody shrubs and trees is an appropriate restorative measure.

But the situation is much more complicated because many factors can limit soil C sequestration. We have seen that C pools have different susceptibility to biological degradation and it is important to understand in which form C is sequestered to comprehend the value of this C. Moreover, the rate of C

sequestration in soil is slow and not linear but, reaching a new equilibrium, soil tends to accumulate C at a slower rate. Freibauer and co-authors [15] report that a new equilibrium can be reached after 20 and 100 years, depending on many factors including the climatic conditions, and thereafter no further change take place. The final level at which the soil C stabilises depends on the soil chemical and physical characteristics, the prevailing climate conditions determining quality and quantity of organic residues and its decomposition, and the balance between C input to soil and C loss through respiration.

Another factor is related to the non-permanent characteristics of soil C sequestered. Land use changes or different soil management determine a rapid loss of C. It is known that the accumulation of C in soil requires stable land use and the benefit of a reduced tillage is lost when a soil is ploughed every 3-4 years. Many authors suggest that the management of land must be permanent to allow C to accumulate.

Among the factors limiting the soil C sequestration we should consider the availability of suitable land and soils and the limited availability of resources as sewage sludge, animal manure or cereal straw. This is implying not only technical and climatic factors but also social and political motivations, involving traditions, habits and behaviour of populations.

7. Conclusion

CO₂ emission from soil is a natural side product due to the biological characteristics of soils. Soil is a living environment, very dynamic with extreme and rapid transformations of organic C. The enhancement of soil organic carbon could be obtained through conservation tillage, mulch farming, cover crops, manuring and compost use, irrigation and restoration of degraded soils, but this has to meet the food demand of growing population. The recommended management practice would lead also to a reduction of the agricultural energy requirements, reducing CO₂ emission from fossil fuel combustion. However, the potential C sequestration is finite. Therefore, it is only a short-term solution. The long-term solution is in reducing CO₂ emission developing alternatives to fossil fuel combustion. On the other hand, the C sequestration is necessary regardless the risks of global warming. Organic C depleted due to past land misuse, and it is something that we cannot afford if we care for the environment and the quality of our life.

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