Carbon Sequestration in Soil

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The agroforestry systems with a high potential for carbon (C) sequestration are those degraded by poor management strategies. Studies on changes in soil C status in these ecosystems mostly take into account labile C pools. Labile and stable soil organic matter (SOM) fractions are affected by soil management and land-use changes. Stable C pools are essential to understanding effects of land-use on soil C storage in the long term.

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1. Introduction

Anthropogenic activities have adversely affected the global carbon (C) cycle and contributed to global climate change. A major driver of recent changes in the earth's climate is the increase in atmospheric carbon dioxide (CO_2). The amount of soil organic C at surface (~1500 Gt C) stored in soil organic matter (SOM) as decomposed plant litter and residues [1] is about three times greater than that of C in the atmosphere. Therefore, the accumulation of C in soil can partially offset the effect of anthropogenic CO_2 emission and is an important strategy to mitigate greenhouse gases (GHG) [2]. The major factors influencing soil C storage are environmental (temperature, precipitation, and soil) and biotic (plant species and composition and anthropogenic activities).

The land use systems were ranked in terms of their soil organic carbon (SOC) concentration by Nair et al. [3] in the order: forest > agroforestry > other tree plantation (e.g., orchards) > arable crops. The transition from an agricultural to an agroforestry system is beneficial to SOC; in contrast, the conversion of secondary and primary forests to agroforestry systems leads to SOC losses [4]. The large differences in C sequestration in soils among land uses reflect the biophysical and socioeconomical characteristics of the system parameters and/or the methodology used. The agroforestry system was recognized by the land use, land use forestry change (LULUCF) as a C sequestration activity, especially under afforestation and reforestation activities. IPCC [5] estimated that 630 million ha of unproductive croplands could be converted to agroforestry worldwide, with the potential to sequester 586,000 t C yr^{-1} by 2040. However, Nair [6] pointed out that there is a significant lack of rigorous data in C sequestration in these systems. To assess changes in SOC stock and storage/loss following a land use change (LUC), some basic data should be considered such as the description of previous land use, SOC stocks, or concentrations and bulk densities in both the previous and new land use, soil depth considered, and time span since conversion [6][7]. The loss of SOC following LUC can be very fast, while usually, it takes a long time to gain. The main difficulty to properly assess SOC changes in agroforestry systems compared to other land uses is associated with the spatial heterogeneity caused by scattered trees and the cultivation of different plant species, which induce different gradients in organic inputs to the soil, and a large number of soil samples are necessary to explore such heterogeneity. Only a few studies have measured the SOC storage in deep soil layers of agroforestry systems [4].

In Europe, and especially in the Mediterranean basin, the abandonment and transformation of large areas of cropland into pastures in recent decades, including agroforestry systems, has been favored with the aim of reducing the surplus of agriculture production and enhancing the C sink capacity of the soils. After the land abandonment, secondary succession vegetation started with pasture colonization affecting strongly the SOC [7][8]. The permanent pastures in agroforestry systems could store 50–60 t C ha^{-1} [9].

However, soils have a limited potential to sequester C (sink saturation) when the annual benefits reach a quasi-equilibrium (steady state) [10][11]. In fact, Dungait et al. [11] reported that it is unlikely that all ancient C in soils can be physically protected because there must be a threshold at which the available C storage niches are filled, referred to as C saturation and defined by the physicochemical properties of the soil. Six et al. [10] reinforced the need for the mechanistic explanation of a saturation level for the unprotected and biochemical protected pools as a priority. In order to account for this, the IPCC [12] recommended at least a 20-year period for soil C sequestration to account for the national GHG inventories.

2. Concepts for Carbon (C) Sequestration in Soil and Understanding the Terminology

Very often, the term “C sequestration” in soil is misunderstood and is used to refer the annual accumulated C in soil (stock). Ideally, the latter should be reported as rate (mass per unit of area and time). Accumulated soil C includes the stable OM pool and the labile (active) OM fraction, with different residence times. The labile fraction is generally more sensitive to soil management changes than the stable OM (passive and recalcitrant), and is then more sensitive than the total SOM [8][13][14]. The labile fraction is constituted by partially decomposed residues and represents 20–50% of the total SOM in cold and semiarid regions [15], and only 10–20% of SOM in tropical and subtropical regions [15][16]. Therefore, the active pool is that which would change mostly in a 1–10-year period. Batjes [17] reported that the most rapid changes in SOM concentration occurred during the first five years after a management practice was imposed, with slower changes occurring thereafter. The passive (recalcitrant) and slow-release OM pools have meant residence times of hundreds to thousands of years [3][18] and are referred as sequestered C in soil.

Based on C dynamics and homogeneity in terms of residence times, SOM may be divided into four pools (**Table 1**): an “active” or “labile” pool of readily oxidized compounds coming from fresh plant material and microbial biomass; a “slowly oxidized pool” (moderate pool) associated with macroaggregates, depending on soil mineralogy and aggregation, as well as agronomic practices; a “very slowly oxidized pool (slow pool)” associated with microaggregates, where the main controlling factor is the water stability of aggregates (agricultural practices have only small effects); and a “passive or recalcitrant pool” where clay mineralogy is the main protecting factor for microbial attack (cultural practices have no relevant effects) [11][13][14][17].

Table 1. Ranges in the amount and turnover times of various types of soil organic matter (SOM) stored in agricultural soils (Source: Batjes [17]).

Type of SOM	Proportion of Total SOM (%)	Turnover Time (Year)	C-Pool
Microbial biomass	2–5	0.1–0.4	labile
Litter	-	1–3	rapid
Particulate organic matter (POM)	18–40	5–20	moderate
Light fraction	10–30	1–15	moderate
Inter-micro-aggregate [a]	20–35	5–50	moderate to slow
Intra-micro-aggregate: [b]			
Physically sequestered	20–40	50–1000	passive
Chemically sequestered	20–40	1000–3000	passive

[a] within macroaggregates, but external to microaggregates, including POM, light fraction, and microbial carbon (C); [b] within microaggregates, including sequestered light fraction and microbial derived C.

The physical protection of SOM includes its occlusion within aggregates and the adsorption onto minerals [11]. The term “humic substances” (humic and fulvic acids, humin) is used to characterize chemically the SOM, humic acid, and humin fractions being considered stabilized/passive and inaccessible to soil microorganism forms [11][19]. Humic substances have been contested by some authors. For instance, Lehmann and Kleber [20] suggested the abandonment of terms related with humic substances because they consider those terms referring to old analytical methods, based on alkaline extraction of SOM fractions. However, Ponge [21] proposed keeping them considering their importance in measuring soil ecosystem services. Therefore, this question is still open. In terms of soil C sequestration, the stability of stored SOM is more important than its quantity. Sequestered C is enhanced when it is in forms physically (e.g., inside the stable microaggregates, forming organo–mineral complexes as secondary particles; this is particularly relevant when 2:1 clay mineral dominates in soil) or chemically protected from microbial activity, or stored in recalcitrant compounds (chitin, cutin, and suberin) with a long turnover, i.e., a slow rate of decomposition [10][11][22][23].

Gabarrón-Galeote et al. [8] described the nonprotected SOC easily decomposable (free POM), with a short turnover time (1–10 years), the physically protected SOC pool by occlusion in stable microaggregates, with an intermediate turnover time (10–100 years); the chemically protected SOC pool by organo–mineral association with silt and clay particles, also with a turnover time of 10–100 years; and a biochemically recalcitrant SOC pool with a turnover time over 100 years. These authors [8] emphasized that knowing the degree of protection of the SOC, expressed as SOC fraction, is crucial for a better understanding of SOC dynamics in soil.

The most basic question is about the C stock increase because there is already a large amount of C stored in soils. Since it is hard to measure a small variation in a large C pool (total SOC) with a high level of precision, an alternative approach would be to select a specific SOC pool within the total SOC as an indicator of change in C stock. Procedures that measure specific physical or chemical labile fractions (i.e., the particulate OM-POM, microbial biomass, and other pools) are useful as indicators of land use changes and for the development of models, but they are complex and time-consuming and would not be run on as many samples as total soil C [18]. Wander et al. [24] reported a greater increment of POM (100%) in the top 5 cm layer of no-tilled silty loam soils than the total SOC (more than 30%).

Consequently, total C measured by the dry combustion (loss in ignition method) or the wet oxidation method [25] is not appropriate to assess components and dynamics regarding soil C stock in the long term issue (C sequestration). Besides being less reliable, these methods are also time-consuming and more dangerous for the environment, and do not discriminate the labile from that corresponding to humic substances and other recalcitrant organic compounds (nonlabile forms). The innovative, nondestructive techniques such as nuclear magnetic resonance (NMR) spectroscopy and inelastic neutron scattering (INS) (technique under development) have a high potential for SOC monitoring in the field. The NMR distinguishes structures that are characteristics of newly formed SOM, in particular the POM in the sand fraction [26][27][28]. This issue remains of critical importance for the C sequestration debate.

Several variations in physical (particle size, aggregate size, or density) and chemical fractionation, or a combination of both, have been employed to separate the more actively cycling (labile SOM) from more stable (recalcitrant SOM) [23]. Because these methods are operational, not functional, none of them perfectly isolate a single active fraction [23]. Both pools can be separated by size and/or density separation. The density fractionation method uses a high-density solution to isolate SOM fractions that differ in stability (separation from soil matrix). It separates soil C into light (>150 μm) and heavy fractions (LF and HF, respectively). The LF is primarily composed of younger plant debris, only partially decomposed and still resembling their original material, but also contains seeds and microbial debris, such as fungal hyphal and spores which are good indicators of labile fraction [10], and including the POM. The LF is controlled by soil management and may be used as an early indicator of effects of soil management changes on SOM [23][29][30]. The HF fraction is composed of amorphous material in an advanced stage of humification associated with soil minerals, forming organo–mineral complexes that are thought to be largely recalcitrant C. Therefore, HF is more crucial to soil C sequestration compared with LF [29][31].

By physical fractionation, particle-size fractions are distributed as coarse sand, fine sand, silt, clay, and particulate organic matter (from the coarse-sand-sized fraction (POM-CS) and fine sand (POM-FS)) [32]. Soil organic matter in the sand or coarser fractions consist of relatively unaltered organic material (POM) [29]. Furthermore, the coarse intra-aggregate POM is physically fragmented and chemically decomposed into fine intra-aggregate POM (in the particle fraction of 50/53–250 μm). This intermediate OM fraction contains fine sand, fine free SOM easily decomposable (POM), stable microaggregates that contain physically stabilized SOC, and biochemically recalcitrant SOM [8][16]. The fine intra-aggregate POM gradually becomes encrusted with silt and clay particles and bound by microbial products (e.g., glomalin, excreted by soil arbuscular mycorrhizal fungi) and is chemically stabilized forming very stable microaggregates (<50/53 μm) within the macroaggregates (<2 mm). The biochemical/protected recalcitrant SOM is crucial for the storage and stabilization of SOC in the long term [8][10][11][22][33][34], contributing to the improvement in soil structure. The physical protection is like a first step in the conservation of SOM that slows down the mineralization process through isolation of microbes from their organic substrates and/or water and O_2 supplies [10][22][35][36]. The size of soil aggregates is usually inversely proportional to the amount of energy needed to disrupt them; then, the microaggregates afford the most protection to the associated SOM [22]. By soil disturbance, like the cultivation practice, the macro- and microaggregates' stabilization can stop, resulting in lower C sequestration in soil [10][22][34]. Then, the loss of SOM is a key factor decreasing the aggregate stability.

Particulate organic matter (POM) is often reported as a stable SOM fraction, but as previously reported, it is not sufficiently stable to explain the long term changes in total SOM [8][10][13].

Nunes et al. [37] used a meta-analysis for soil management assessment framework (SMAF) as a comprehensive tool to assess the effects of land use and management practices on soil health by integrating multifunctional indicators (e.g., SOC, aggregate stability, microbial C, pH, P, and bulk density) which represent the important soil functions. They confirmed that tillage generally decreased SOC content by disrupting soil aggregates, by increasing mineralization rates (i.e., oxidation of C), and by exposing bare soils to erosion from water and wind. In addition, the long term loss of SOC led to reduced soil biological activity, aggregate stability, water storage, and incrusting surface crusting and erosion. They advertised that conversion of conventional tillage to no-tillage improved biological and physical indicators of soil health in the topsoil, likely due to the maintenance of crop residues on the soil surface, and a subsequent increase in SOM. Finally, they recommended that converting annual cropping systems to perennial systems is a strategy to enhance long term agroecosystem sustainability, environmental protection, and climate change resilience.

Actual measurements to understand SOM pool sizes, and how they will change with management systems, might be of great relevance and interest for policymakers and traders of C credits. Such measurements can be taken by modeling (e.g., the Q model, particularly advantageous under changing climatic conditions; the Roth C model, where "DPM" represents the decomposing plant material and "BIO" represents the biomass pools and simulates the physical protection in the long term; and the Century model, where the metabolic compounds are associated with the "active" and "metabolic" pools) [11]. However, modeling can only be achieved if there is a large number of on-site measurements at specific sites to verify the model. Soil sampling and analytical methods require further studies. The nondestructive techniques under development would probably be of high importance for this purpose.

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