

Component of soil carbon and formation of aggregate

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Abstract. Carbon dioxide (CO₂) take a large proportion of air. The concentration of CO₂ improved from 317 ppm in 1958 to 405 ppm in 2016. It is a global challenge to control and reduce the concentration of CO₂. Soil carbon pool is the second major pool of carbon on the earth and has considerable potential to sequester CO₂. This paper concentrates on the mechanism of soil carbon sequestration including the composition of soil organic matter, existence form, protection mechanism and model of aggregates.

Keywords. Soil, carbon sequestration, mechanism, aggregates

1. Introduction

Global warming has been a worldwide challenge, which mainly caused by the improvement concentration of carbon dioxide (CO₂) in atmosphere. Control and reduction the concentration of carbon dioxide become more and more important for sustainable development. From last 70s, some researchers began to calculate the global storage of organic carbon. In 1980s, researchers concentrated on the influence factors of different ecosystem to carbon sequestration. Later, to model the change of soil carbon storage, there started the division of soil carbon pools and corresponding physical and chemical property. Subsequently, researchers mainly focus on the temperature sensitivity of SOC indifferent soil types and the stable mechanism[1].

Organic carbon pool on the earth can be divided into ocean pool, soil pool and biomass pool, which contains about 384000Gt, 2344Gt and 560Gt (gigaton) organic carbon correspondingly[2]. Soil, as the world's second largest carbon pool, has significant role to regulate global climate. Soil carbon sequestration means underground organic matter and atmospheric carbon dioxide translate into another formation which is preserved in soil stably. Translation include physical and chemical reaction[3]. Soil carbon pool contains huger number of carbon, which is vulnerable to the change of climate and land management mode. While, a slight variation of soil carbon pool can further affect the concentration of carbon dioxide in the atmosphere. Therefore, researches on the mechanism of soil carbon sequestration are important basis for improving the quantity of steady soil carbon.

Soil carbon (SC) pool includes soil organic carbon (SOC) and soil inorganic carbon (SIC). According to an estimate[4], the global content of organic carbon and inorganic carbon is 1550 Gt and 950 Gt, respectively. There are deviations between the results of different researchers since they use different ways to estimate the global soil carbon. The stabilization mechanism of organic carbon and inorganic carbon are quite different. As shown in Figure 1, plants absorb carbon dioxide from the air through photosynthesis. Then, carbon is fixed in the plant roots, branches and leaves. Leaves, dead roots and other organic matters gradually decomposed under the action of microorganisms. Through the action with soil particles, these organic matters will combine with soil and form stable and persistent soil organic carbon. This is the nuclear fixation process of soil organic carbon. Soil inorganic carbon formation mainly through the action between carbon dioxide in the air, cation in the soil and water, which means the main constituent of inorganic carbon is carbonate. The proportion of soil organic carbon and inorganic carbon is different in different regions. For example, soil organic carbon mainly exists in humid area, while inorganic carbon is dominant in arid area. In this paper, the mechanism of soil organic carbon sequestration is mainly discussed.

2. Composition of soil organic carbon

There are different sources of organic matter in the soil. Part of them are released into the air due to decomposition, others are stored in the soil with a stable form through physical and chemical interaction with the soil particles. Quantifying and increasing soil carbon sequestration requires understanding what forms of organic matter are present in the soil. According to a large number of studies, SOC mainly includes plant residues and rhizodeposition.

Plant residues are mainly produced in the process of plant growth, including plant leaves, limbs, roots and dead roots and so on. In the natural environment, deciduous leaves are one of the main forms of organic matter input in surface soil. In cultivated land, the residual roots of the crop after harvest will remain in the soil for further decomposition. Besides, plant stems are raw materials of organic fertilizer in some of arable land. These are the modes of soil organic matter input.

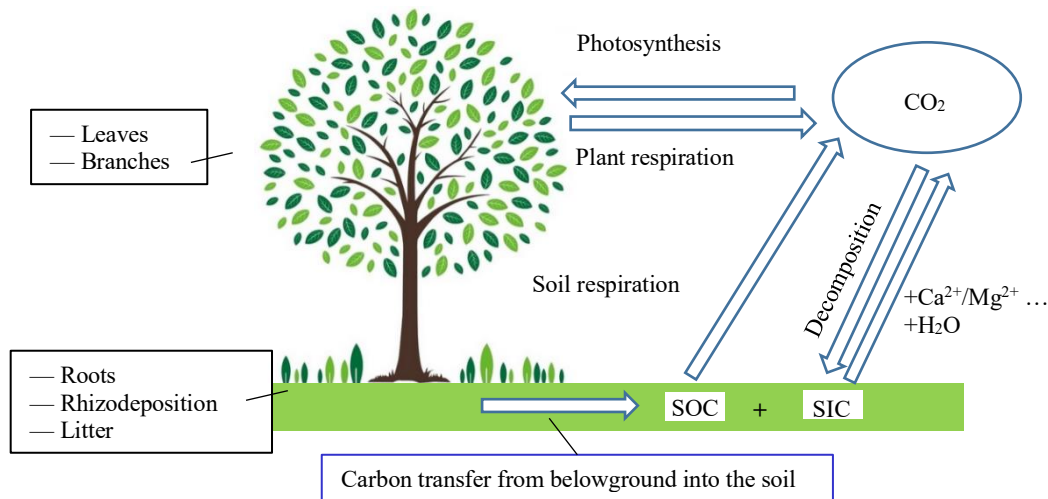


Figure 1. The carbon cycle in nature

Rhizodeposition refers to the organic matter that is released to the soil through the roots during plant growth[5]. About 3-6% of the carbon from plant photosynthesis is transferred to the soil[6]. While another research^[7] find that about 20-40% of the carbon from plant photosynthesis is transferred to the underground. 2-18% of them will become soil organic carbon, the rest form root tissue or release through the root respiration. These two conclusions are similar after ratio conversion.

Rhizodeposition includes root mucilage, root exudate, border cells loss, dead or dissolved root cells and lost organic carbon through rhizospheric symbiotic mycorrhiza[7]. These classifications are only theoretically because they are difficult to extract separately in experiment.

1) Root mucilage

The root cap cells of the plant secreted mucilage through the extracellular secretion and formed a gel layer outside the root cap. The composition of the mucilage is polysaccharide[8]. Root mucilage secretion plays an important role in regulating the root environment. Research[9] has shown that carboxylic acid groups in the mucus can bind to toxic metals, thus protecting the root meristem. In addition, mucilage reduces soil erosion and enhances soil ventilation by increasing the stability of soil aggregates which is benefit for promoting root growth[10]. Root mucilage has terrific water absorbability, its water content can reach 100,000 times of its dry weight[11]. This feature can maintain more water for the roots [12] and reduce the friction resistance during root cap growth[13].

2) Root exudate

Root exudate is a kind of diffuse compound that is passively lost from the roots of plants. It mainly consists of free sugars (glucose, sucrose), amino acids (glycine, glutamic acid) and organic acids (citrate, malate, oxalate). Leakage rate of exudate depends on three factors: root-soil concentration gradient, cell membrane permeability and solute position in the root tissue. Concentration of organic matter in the soil will be lower than in the roots because organic matter in the soil is decomposed constantly by microbes and organic matter in the root tissues is continuously produced. However, the dominant fact of exudate lost is concentration gradient between cytoplasm and cell wall, but not the concentration gradient between root and soil[14].

3) Border cells

Border cells refer to the cells that are isolated from the outer layer of root cap and are continuously renewed. Study had shown that the separation of border cells can reduce the friction when root tip are growing[15]. The rate of border cells detachment have greater differences due to the variety of plant species and growth environment. Lost border cells will survive in the soil for a few days after leaving root tissue, meanwhile, they are surrounded by the mucus secreted by themselves. The mucus can combine with heavy metals in soil to protect root system from heavy metal contamination[16]. Another benefit of border cells is generating signifier to resist pathogens, thus protecting the meristem and regulating the growth environment of the root system[17].

4) Dead or dissolved root cells

In the process of plant growth, part of the root epidermis will degrade and release organic matter to the soil[18]. It is generally believed that infection of pathogens and root wear are the cause of cell death. The amount of organic matter entering the soil is usually quantified by determining the amount of epidermal cells loss. There is a positive correlation between the diameter of the root and the lifetime of the root[19]. Therefore, the amount of the input soil organic carbon can be calculated according to the amount of fine roots.

5) Mycorrhiza

Many plants can form symbiosis with mycorrhizal fungi like legume. The carbon lost through the rhizosphere symbiosis mainly in two forms: the constituent parts of the hyphae structure and the exudates that flow away to the rhizosphere through hyphae.

3. Protection of soil organic carbon

Stabilization of organic matter in soil mainly achieve through two ways: Organic-mineral complex and physical protection.

1) Organic-mineral complex

As shown in Figure 2, clay minerals combine with soil organic matter through multivalent cations (Fe^{2+} , Mg^{2+} , Al^{3+} , etc.), hydrogen bond and van der Waals force, that is stable organic-mineral complexes[20]. Such complexes are resistant to biodegradation, thus allowing organic matter to be stored in soil for long periods of time[21].

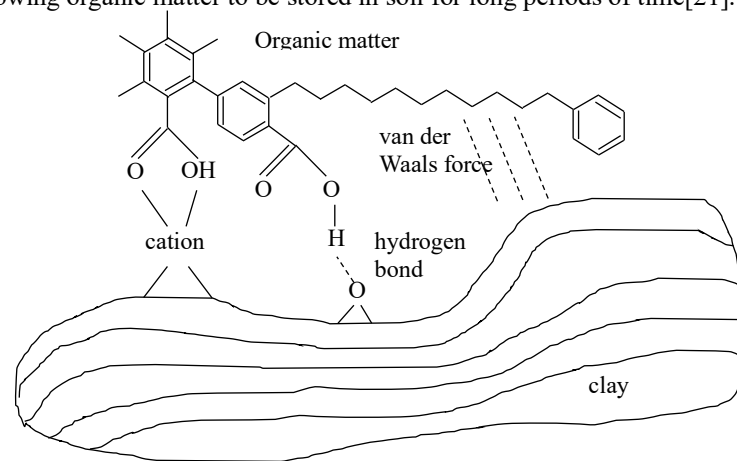


Figure 2. Organic-mineral complex

Mineral composition and structure of soil particles in different sizes is different and they combine with organic carbon in specific patterns. So the amount and composition of protected organic carbon can be determined by soil particles sizes[22]. It's concluded that soil organic carbon content related to clay, silt and sand were 3.68%, 3.27% and 1.93% respectively[23]. It is believed that high content of SOC in clay is content is due to large specific surface area of clay[24].

The capacity of sequestering carbon varies in mineral structure. Based on the difference of the interface between mineral and soil[25], mineral can be divided into three types:

- Hydroxyl surface like Fe/Al oxide.
- Siloxane surface with electrical layer like 1:2 layered silicate structure (illite, montmorillonite).
- Siloxane surface without electrical layer like 1:1 layered silicate structure (kaolinite).

Compared to montmorillonite and kaolinite, the stabilization of SOC by Fe/Al oxides is better in acidic soils[26]. Fe/Al oxides immobilize SOC mainly through the connect of organic acids and hydroxyl groups on the surface. Montmorillonite has a greater specific surface area and cation exchange capacity (CEC) than kaolinite, so it contains more SOC[27]. Besides, the organic matter connected with kaolinite contains more polysaccharides, while the organics connected with montmorillonite contain more arene compounds[28].

2) Physical protection

Physical protection of organic matter is achieved mainly through the formation of aggregates. Aggregates means cementation reunion between soil particles and organic matter. Agglomeration of organic matter and soil particles will reduce the decomposition form microbial, which is similar to formation of physical crust outside the organic matter. According to diameter size, aggregates are divided into macroaggregates ($> 250\mu\text{m}$) and microaggregates ($< 250\mu\text{m}$)[29]. Macroaggregates containe more organic carbon than microaggregates, but the turnover time of organic carbon in aggregates increased with the decrease of aggregates size[30]. The protective effect of microaggregates on organic carbon was related to the connection strength of the organic-mineral complex. Mineral-bound organic carbon will continue to adsorb other soil particles to form aggregates until organic matters are wrapped within the aggregates which means physical protection[23]. However, the proportion of physical protection and organic-mineral combination is not clear.

4. Mechanism of soil aggregates

4.1 Binding agent of aggregates

The formation of aggregates are directly related to the amount and decomposition degree of plant residues in the soil. These substances act as binding agent within aggregates. There are three types of connection media: temporary binding agent, transient binding agent and persistent binding agent[31].

1) Temporary binding agent

Temporary binding agent mainly includes plant root, fungal mycelium, mycorrhizal hyphae and so on. Growth of plant roots and mycelium form the initial large aggregate through the establishment of the visible organic skeleton to absorb mineral particles. After partial decomposition, released fine roots, root hair, mucilage will adsorb clay particles to enhance macroaggregates (Figure 3). This process plays a major role in the beginning of maroaggregates.



Figure 3. Aggregate connected by root

2) Transient binding agent

Transient binding agent mainly includes polysaccharide and organic mucilage. It is derived from plant tissues, root mucilage, root exudate, fungal hyphae and bacteria. Its effect on aggregates usually lasts only a few weeks because it is easy to be decomposed, but it is very important for the formation of soil aggregates.

Polysaccharides typically link aggregates of $10 - 50\mu\text{m}$ by the bridge of polymers. Polysaccharides are more likely to be adsorbed by clay particles, compared to humic acids and organic acids[32]. The negative charge on the polysaccharide surface makes it stable when binding to clay particles. In addition polysaccharide can increase the tensile and anti-cracking strength of clay mineral aggregate[33]. Since the polysaccharide will not be decomposed in a short period of time, it acts as transient binding agent to connect clay particles and organic matters in the large aggregate.

3) Persistent binding agent

Persistent binding agent is a highly decomposed organic matter, including humus, polymers and multivalent cations. The combination of organic, polyvalent cations (Al^{3+} , Fe^{3+} , Ca^{2+} , ...) and minerals can generate stable microaggregates[29]. On the one hand, polyvalent cation is adsorbed by the negatively charged on the surface of clay particles, and on the other hand, chelates with the carboxyl or hydroxyl groups on the surface of organic matters. The microaggregates stabled by persistent binding agent are the main forms of long-term preserved soil organic carbon.

4.2 Model of aggregates

Before 1984, traditional model believed that the formation of microaggregates was before the formation of macroaggregates, and the aggregation of microaggregates formed macroaggregates[29–34]. The most representative model of aggregate formation was proposed by Tisdall and Oades in 1982[31]. In Figure 4, this model divides soil aggregates into five stages: $< 0.2\mu\text{m}$, $0.2 - 2\mu\text{m}$, $2 - 20\mu\text{m}$, $20 - 250\mu\text{m}$ and $> 2000\mu\text{m}$. The aggregates of these five stages gradually accumulate from small to large.

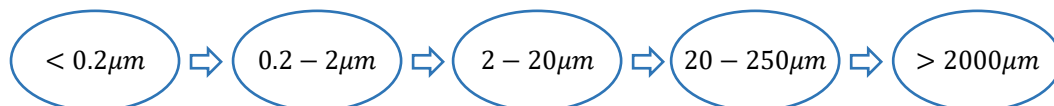


Figure 4. Traditional aggregate model

However, in 1984, Oades made a major revision to the previous theoretical model. The new model[35] suggests that soil particles form large aggregates through the connection of plant roots and hyphae first. However, plant roots and hyphae are temporary binding agent and will be decomposed in one year. As the plant roots and mycelia decompose, the broken fragments become the center of the large particles, and the large aggregates break down. The mucilage and the clay occurred in process of decomposition interact with each other, and then form crusts outside the organic fragments until the decomposition becomes slow and eventually forms microaggregates.

Six proposed a new aggregates transformation models after studying the effects of tillage on aggregate (Figure 5) [36].

Phase ①: Fresh residues combined with soil particles to form macroaggregates. Due to the decomposition of microorganisms, the residue was gradually converted into internal particulate organic matter. The hyphae and mucus produced during the decomposition acted as a temporary medium, making the large aggregates more stable.

Phase ②: Some coarse particle organic matters were decomposed into fine particle organic matters.

Phase ③: Small particles of organic matters were gradually wrapped and crusted by clay particles and microbial products, which was the formation of micro-aggregates. The organic matters within the microaggregates were protected from the decomposition due to this protective layer.

Phase ④: The stability of large aggregates lost as the temporary binding agents disappeared, which used to connect large aggregates. Stable microaggregates were released after macroaggregates broken.

Phase ⑤: Some microaggregates were going to participate next formation cycle of macroaggregates.

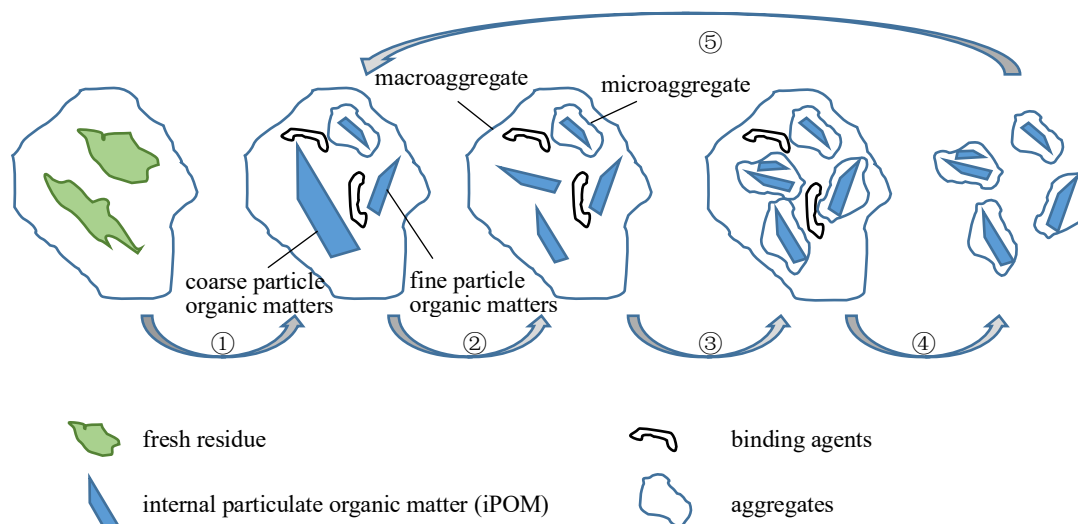


Figure 5. Model of aggregate transformation

5. Conclusion

Many researches about the mechanism of soil carbon sequestration have been done, but there are still some problems. Most studies of microaggregates focused on aggregates in the range of 50 – 250 μm , while studies about smaller aggregates were lacked^[23]. For different soil types of various land cover, it is still unknown to understand the exact mechanism of soil carbon transformation to stable or unstable carbon pool. There is no standard way to distinguish between stable soil carbon pool and non-stable soil carbon pool, so it's hard to get scientific conclusion on the sensitivity to different climatic factors of the two pools^[1]. Future studies on soil carbon sequestration need pay more attention to the dynamic change of soil carbon pool and how to increase soil carbon content by changing land management model.

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